Title: Gravity and Yang-Mills Sectors from a Unified Theory and Their Relation with Dark Energy

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URL: http://pirsa.org/12050079

Abstract: We propose a new method of unifying gravity and the Yang-Mills fields by introducing a spin-foam model. We realize a unification between an SU(2) Yang-Mills interaction and 3D general relativity by considering a constrained Spin(4) ~SO(4) Plebanski action. The theory is quantized a la spin-foam by implementing the analogue of the simplicial constraints for the Spin(4) symmetry, providing a way to couple Yang-Mills fields to spin-foams. We also present a way to recover 2-point correlation functions between the connections as a first way to implement scattering amplitudes between particle states. We conclude with speculations about extension of the model to 4D and incorporate a newly developed model of Dark Energy.

Outline

- Introduction and motivations
- Physical consequences of Unification: two models
- 3D reduction and Coleman-Mandula theorem
- Plebanski Spin(4) theory and symmetry breaking
- Spin Foam quantization
- Coherent States for GR and YM sectors: interpretation
- Boundary formalism and holonomies 2-point function
- Generalization to 4D and other YM sectors
- DE as a physical context to apply the unified fram
- Summary and Conclusions

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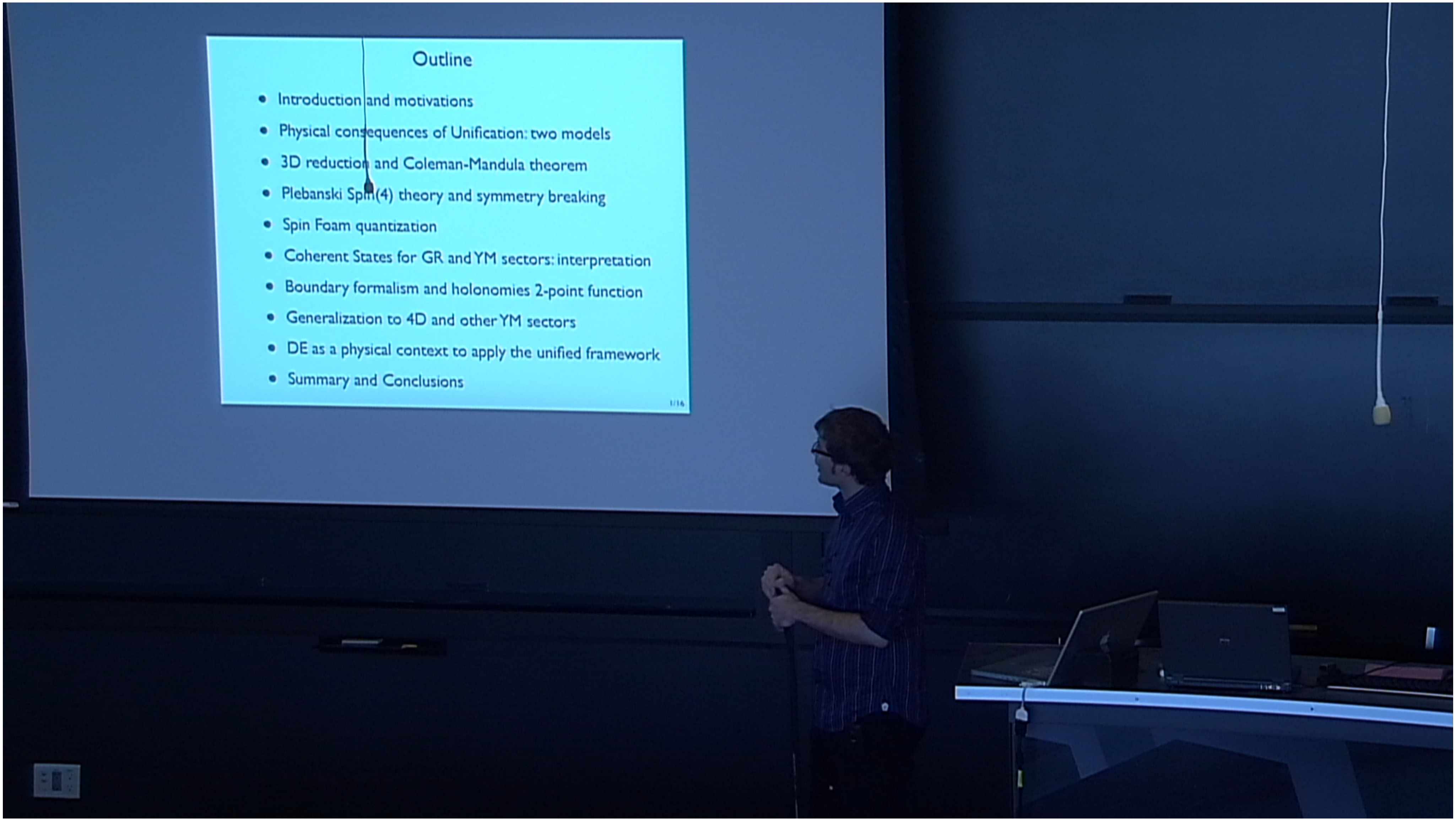
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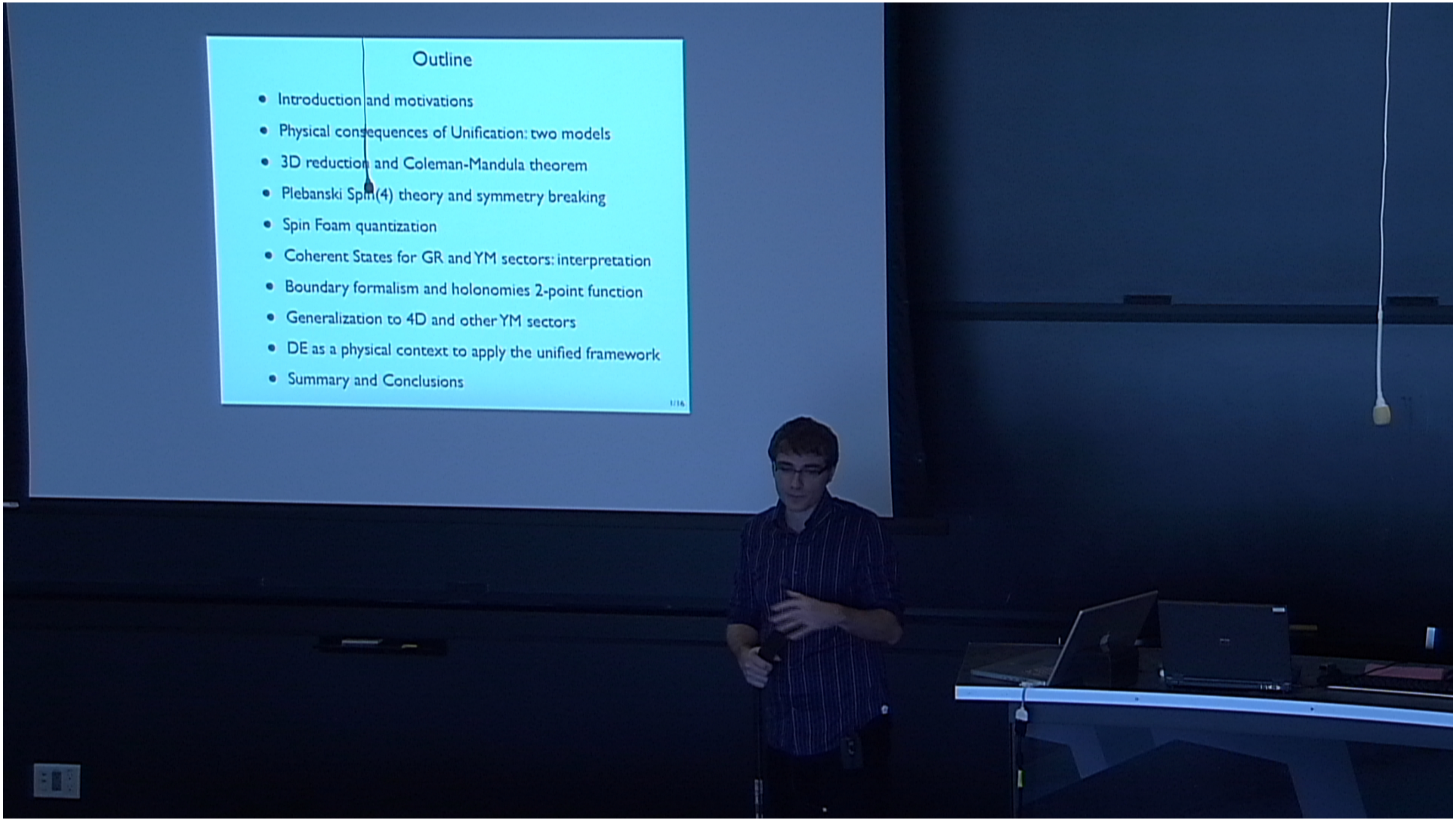
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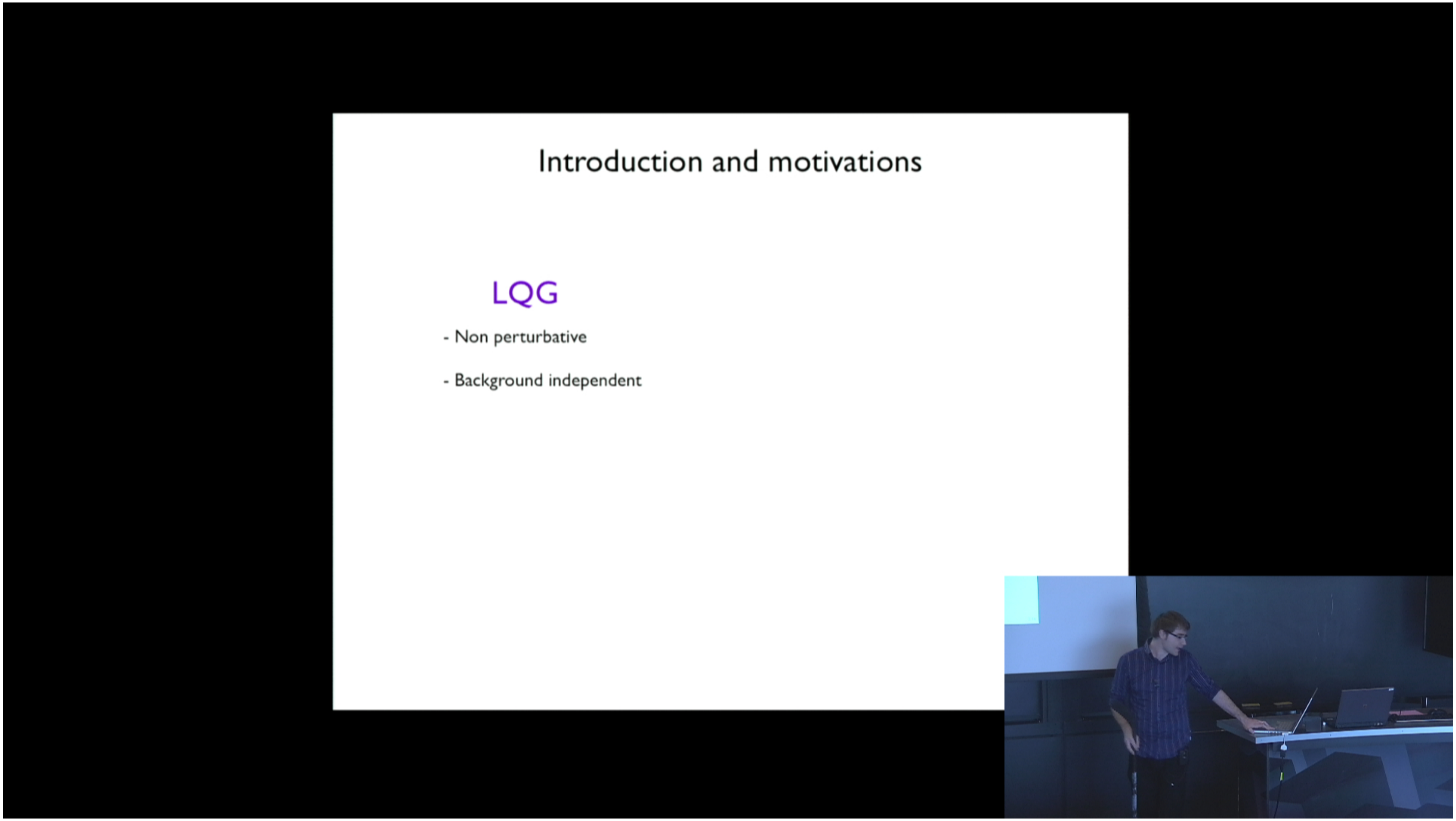
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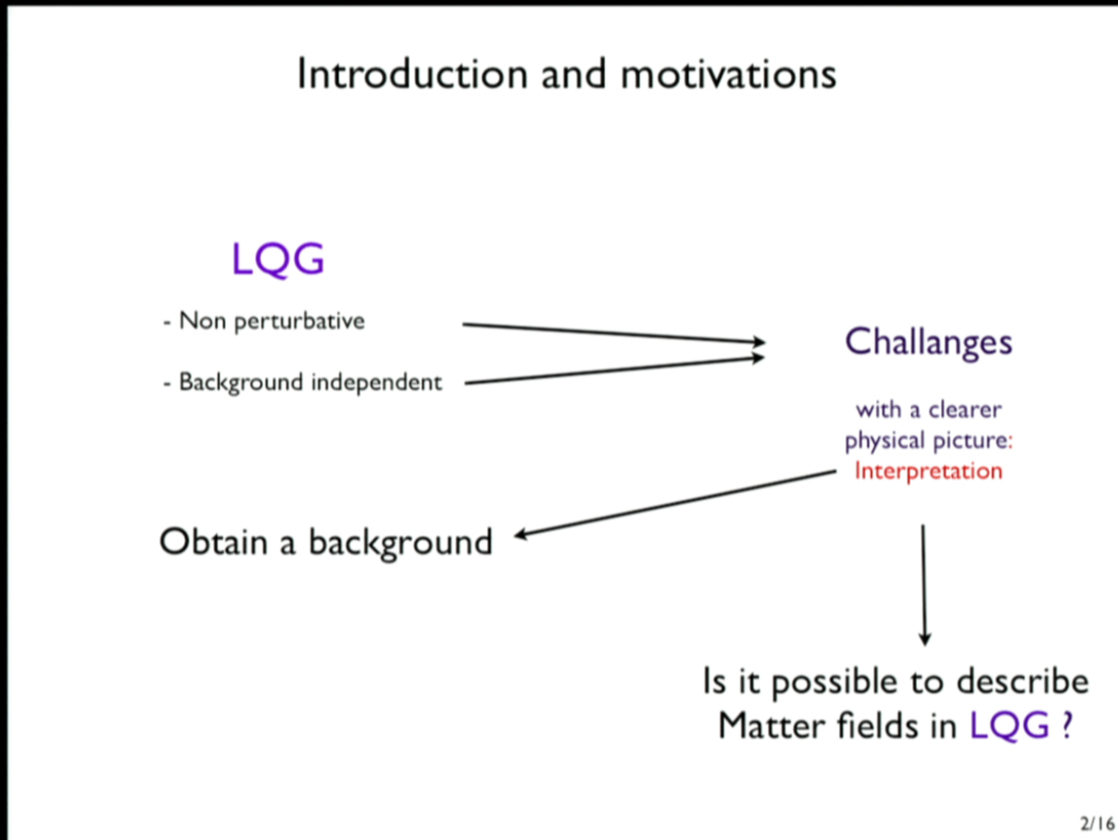
- Background independent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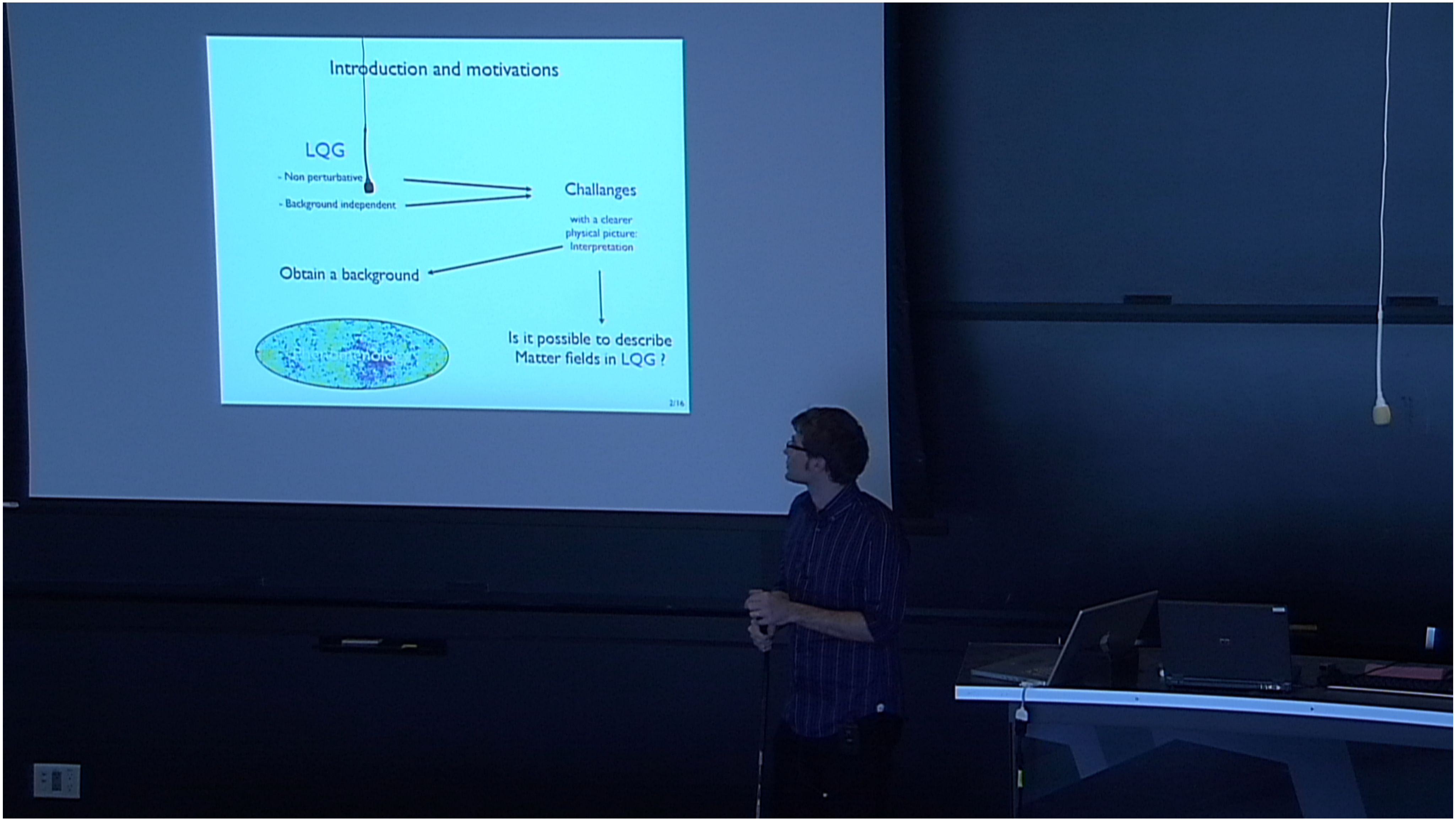
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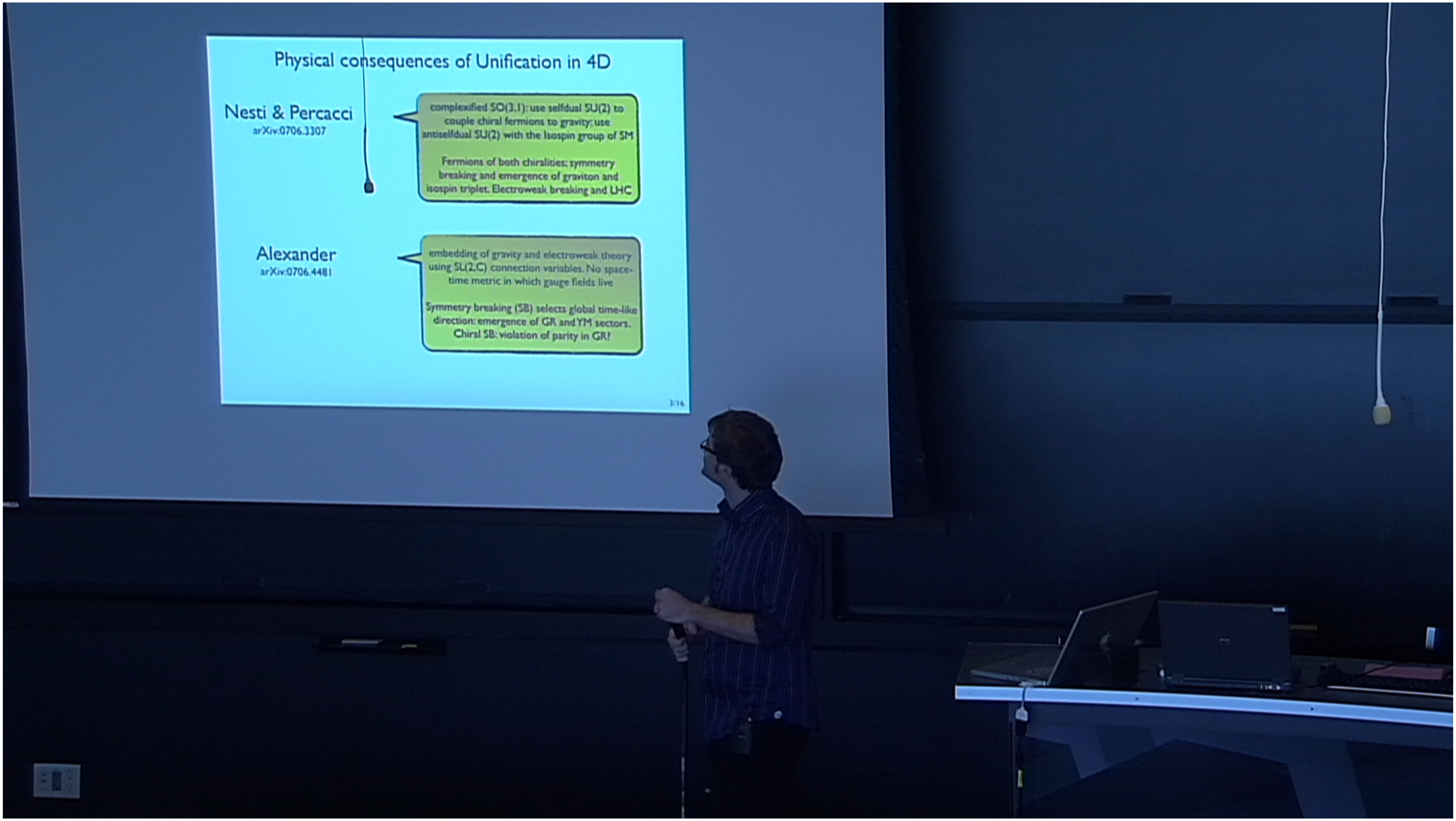
Physical consequences of Unification in 4D
Nesti & Percacci
arXiv:0706.3307
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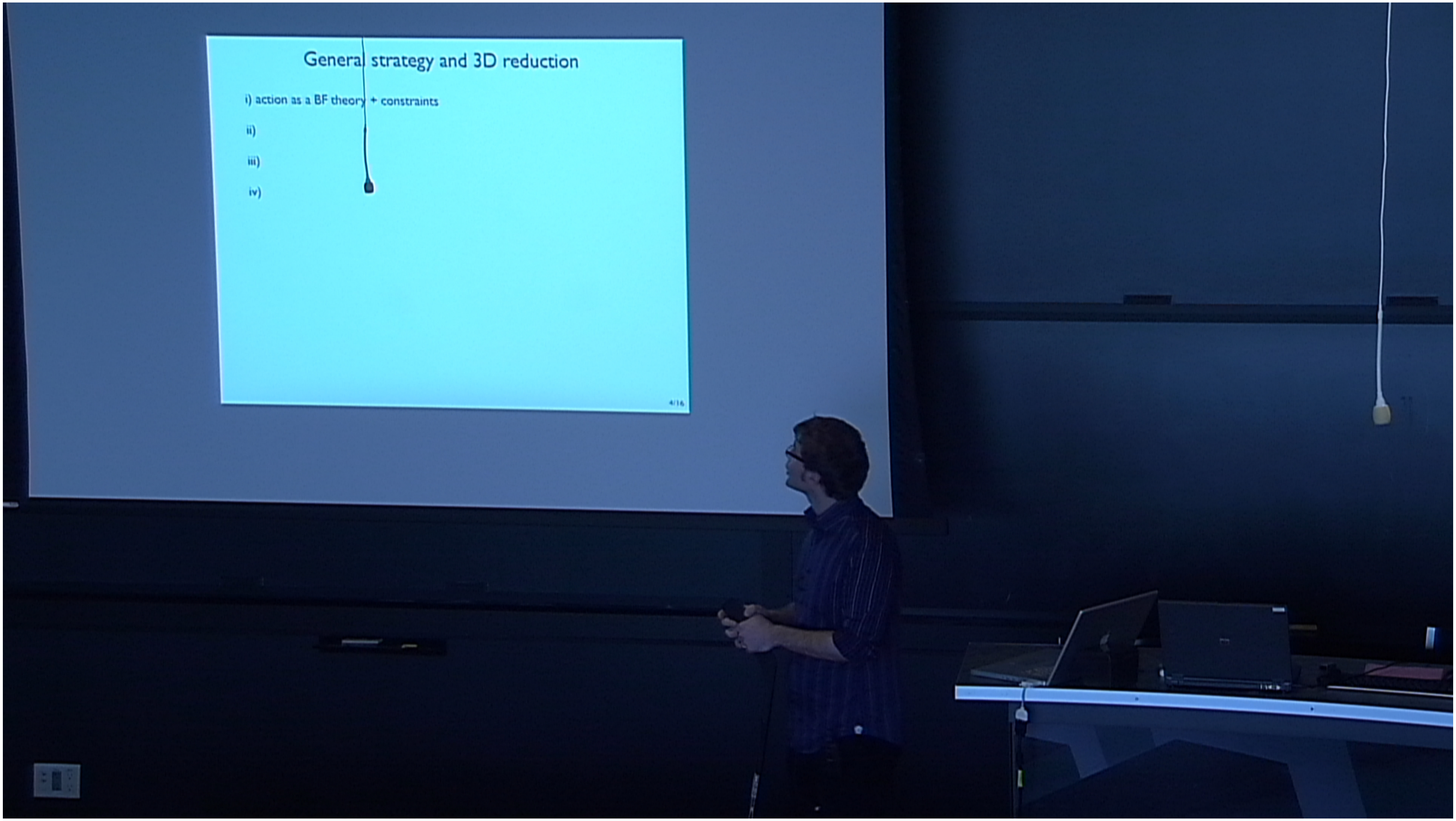
Main message: correlation in reduced phase-space sectors.
A similar story: B-I parameter and chirality (Magueijo Benincasa) 3/16


General strategy and 3D reduction
i) action as a BF theory + constraints
ii)
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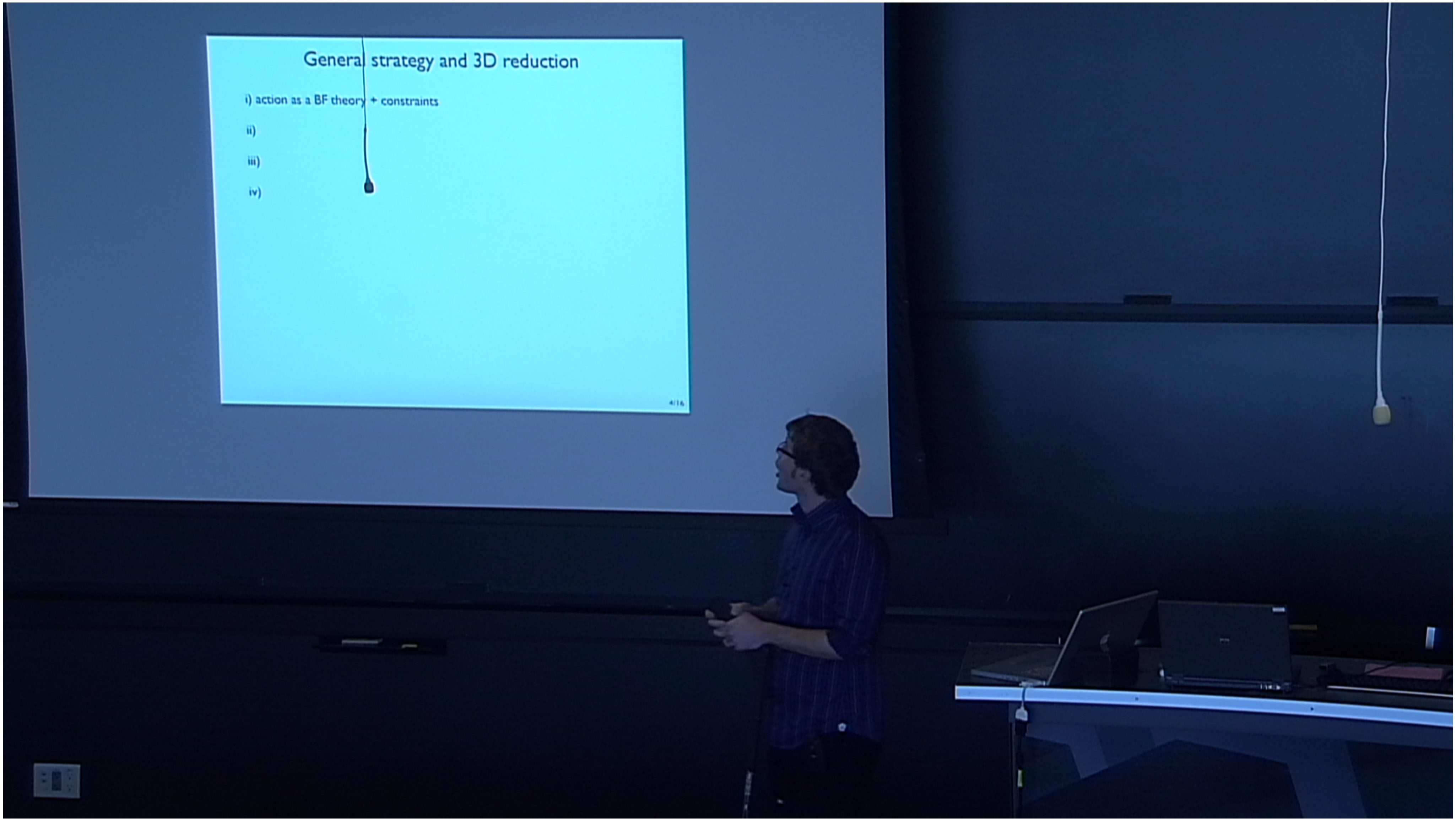
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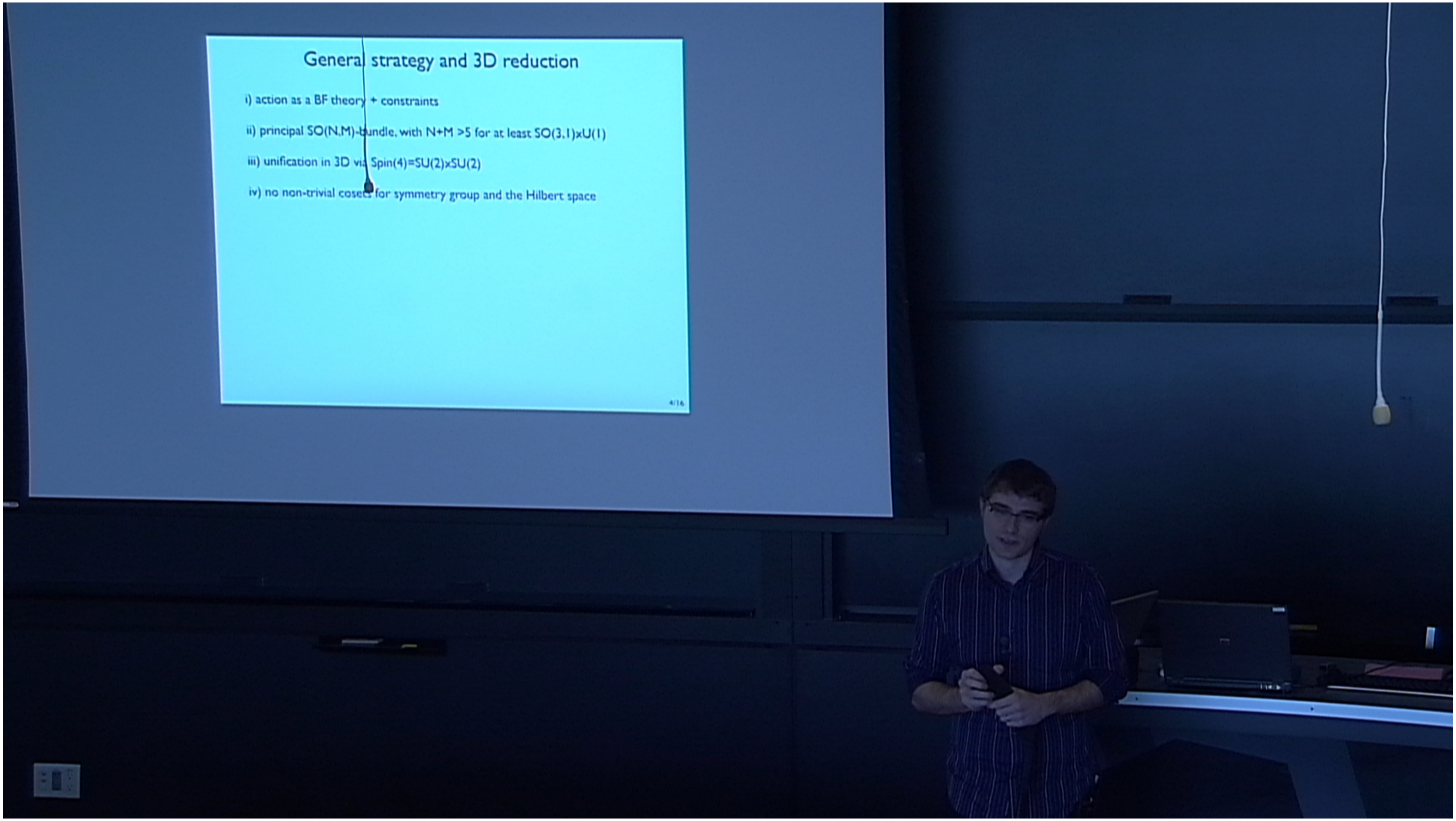
iv) no non-trivial cosets for symmetry group and the Hilbert space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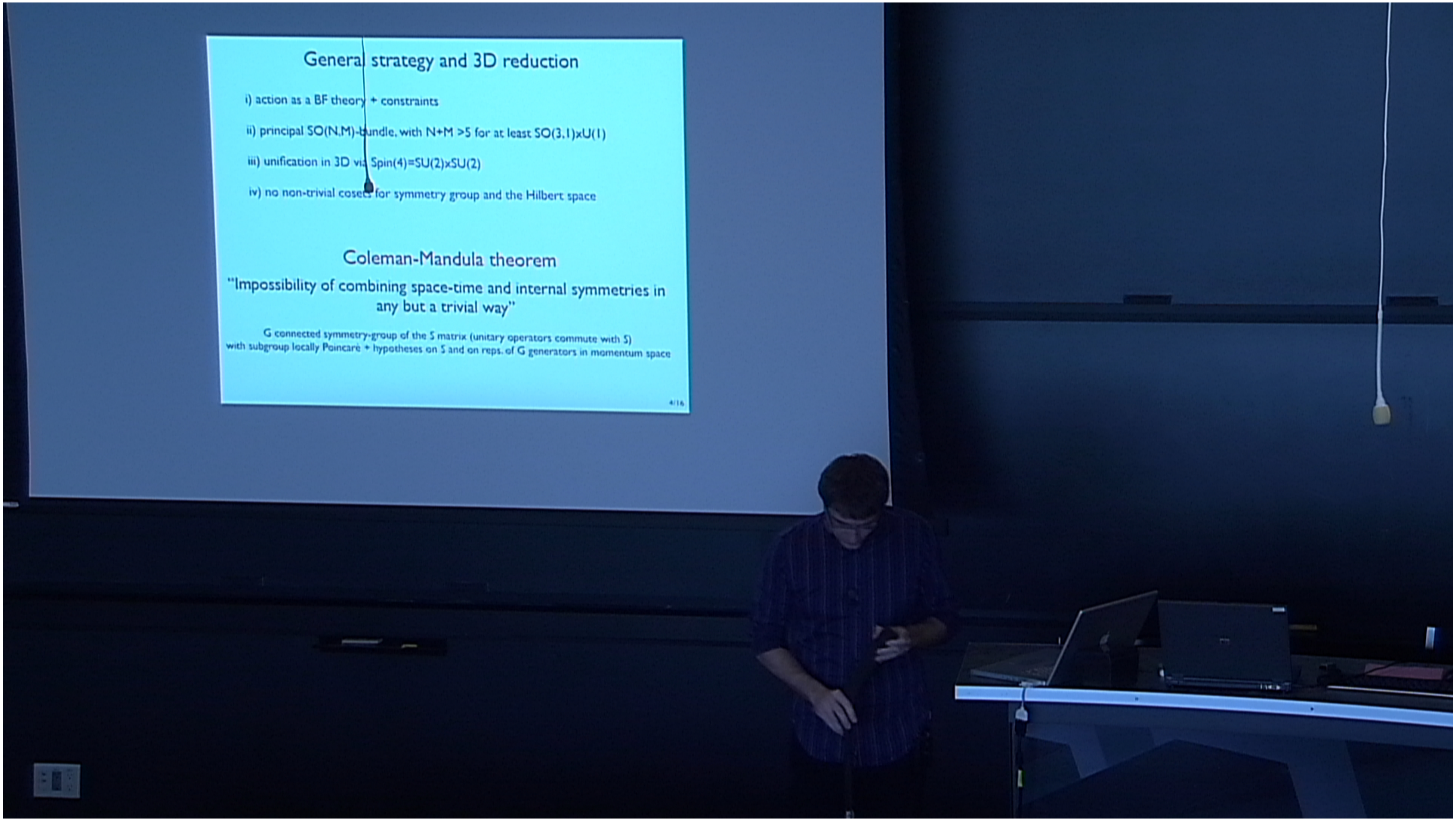
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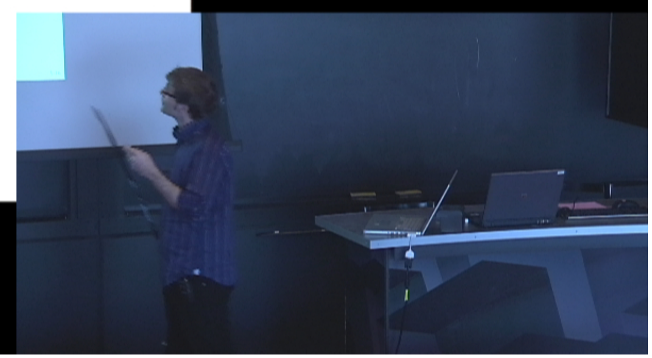
Coleman-Mandula theorem
"Impossibility of combining space-time and internal symmetries in any but a trivial way"
G connected symmetry-group of the S matrix (unitary operators commute with S)
with subgroup locally Poincaré + hypotheses on S and on reps. of G generators in momentum space
4/16

Plebanski Spin(4) theory and Symmetry breaking

$$S^{Pleb} = \frac{1}{G}\int_{\mathcal{M}_3} B^I \wedge F_I(A) - \Phi \cdot \mathcal{B} + g\,\Phi \cdot \mathcal{B}\,(\Phi \cdot \Phi)$$



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$\mathcal{B}^{IJK} \equiv B^I \wedge B^J \wedge B^K$

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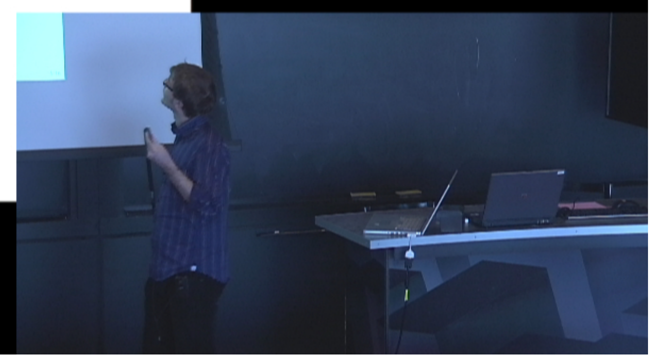
$\mathcal{D}_A \wedge B^I = 0$

$\mathcal{B}^{IJK}\,(1 - g\,\Phi \cdot \Phi) - 2g\,(\Phi \cdot \mathcal{B})\,\Phi^{IJK} = 0$

$F_I = \Phi_{IJK} B^J \wedge B^K (1 - g\Phi \cdot \Phi)$



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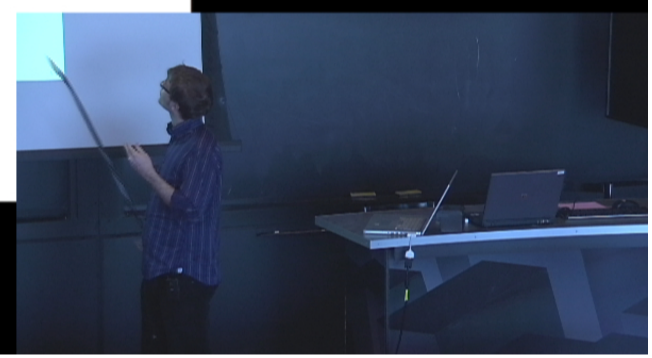

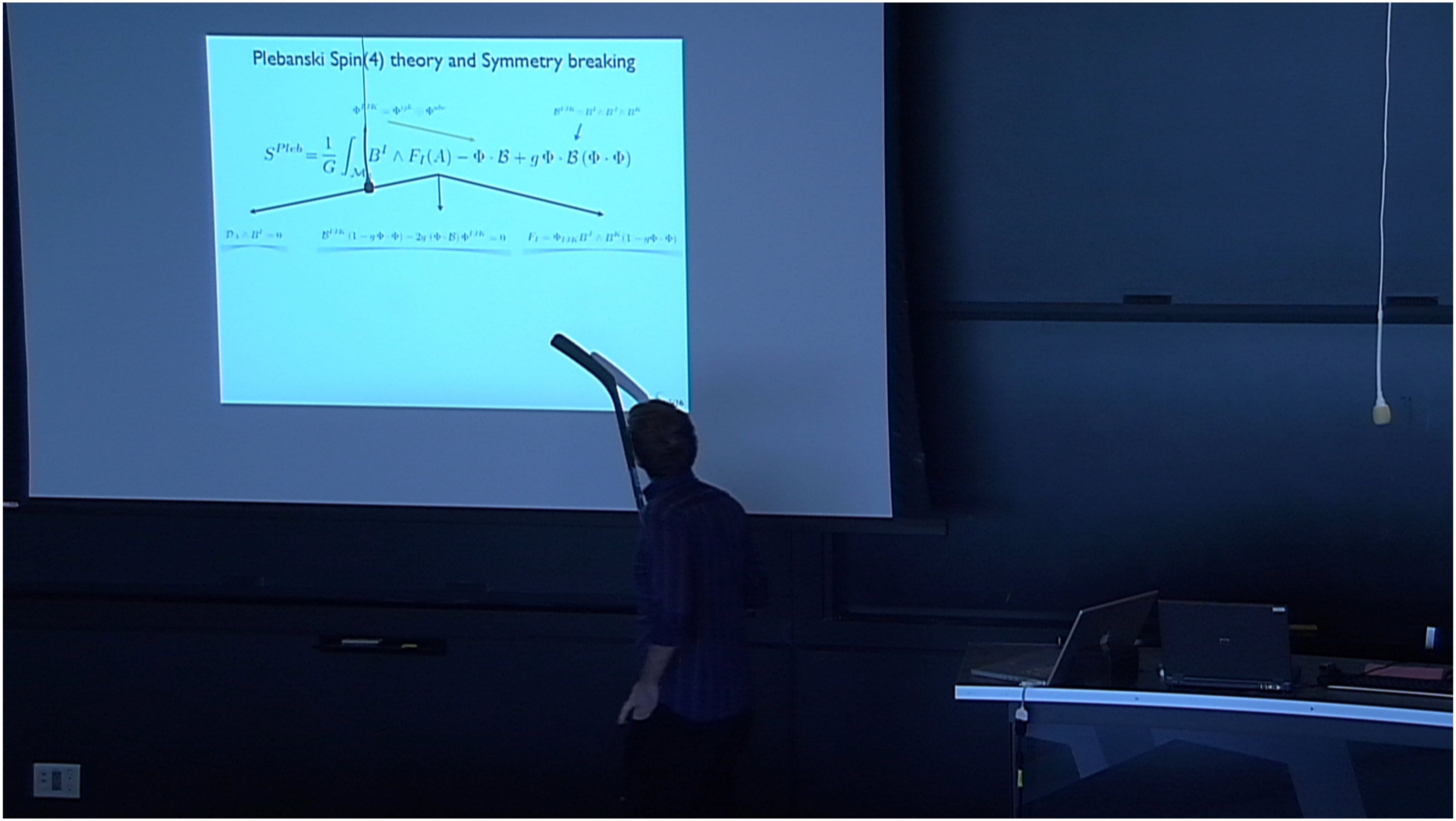
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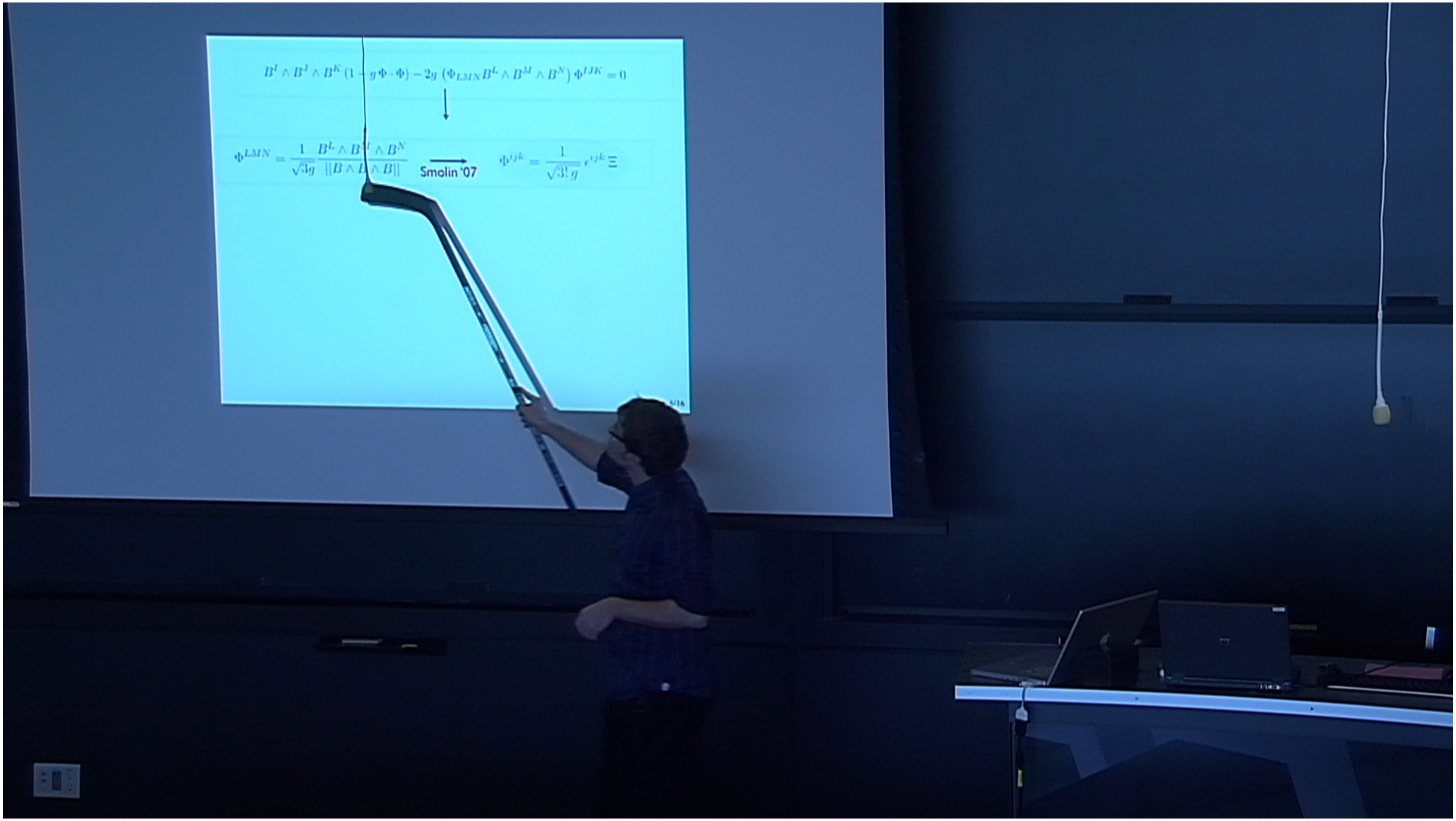
$B^I \wedge B^J \wedge B^K (1 - g\Phi \cdot \Phi) - 2g\left(\Phi_{LMN} B^L \wedge B^M \wedge B^N\right)\Phi^{IJK} = 0$
$\Phi^{LMN} = \frac{1}{\sqrt{3}g} \frac{B^L \wedge B^M \wedge B^N}{||B \wedge B \wedge B||}$
Smolin '07
$\Phi^{ijk} = \frac{1}{\sqrt{3!}\,g}\,\epsilon^{ijk}\,\Xi$
6/16

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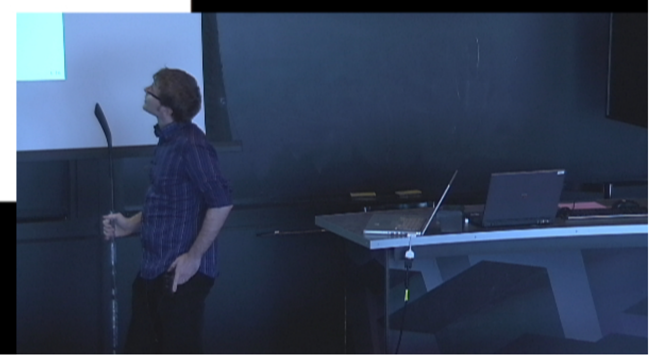

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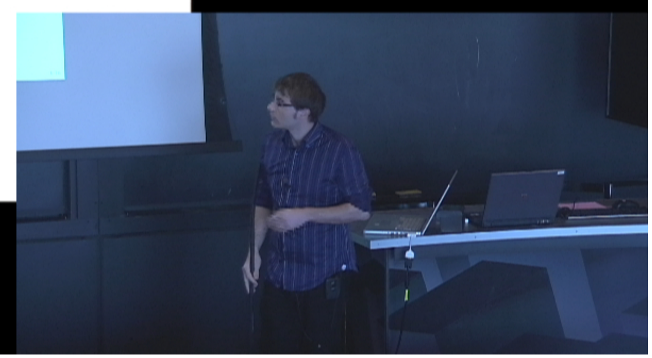

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$$\Phi^{ijk} = \frac{1}{\sqrt{3!\,g}}\,\epsilon^{ijk}\,\Xi$$

$$B^i \wedge B^j \wedge B^k (1 - \Xi^2) = 2\,\frac{\Xi^2}{3!}\,\left(\epsilon_{lmn} B^l \wedge B^m \wedge B^n\right)\,\epsilon^{ijk}$$

$$B^i \wedge B^j \wedge B^k \left[1 - g\left(\Phi^{ijk}\Phi_{ijk} + \Phi^{abc}\Phi_{abc}\right)\right] =$$

$$= -2g\left[\Phi_{ijk}\,B^i \wedge B^j \wedge B^k + \Phi_{abc}\,B^a \wedge B^b \wedge B^c\right]\,\frac{1}{3\sqrt{2\,g}}\,\epsilon^{ijk}$$

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$$\downarrow$$

$$\tfrac{2}{3}\epsilon_{ijk}\, B^i \wedge B^j \wedge B^k \left(1 - 9\, g \lambda^2\right) =$$

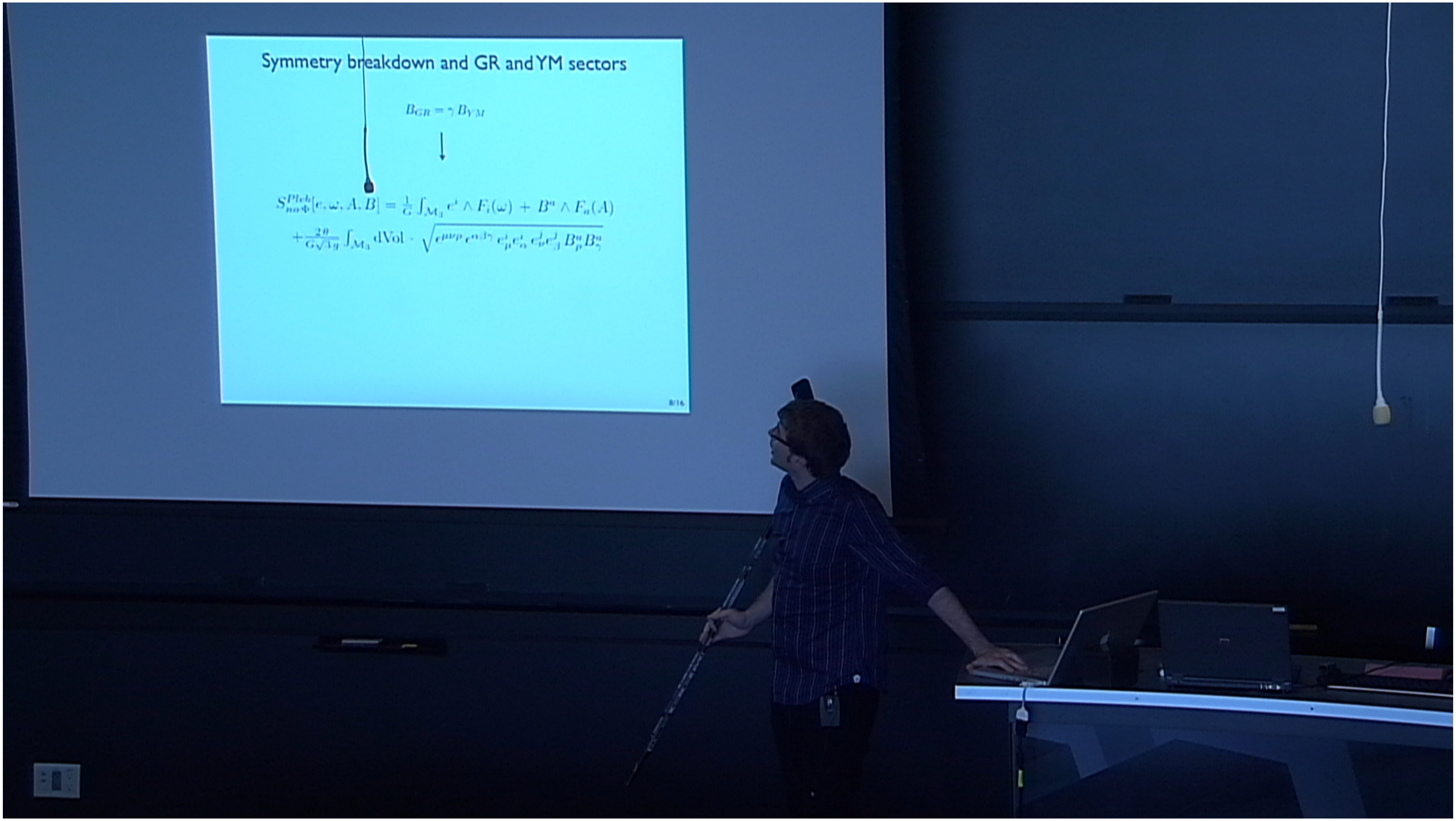
$$= -\tfrac{2}{3}\left(-\epsilon_{ijk}\, B^i \wedge B^j \wedge B^k + 3\sqrt{2}\,\sqrt{g}\,\lambda\,\epsilon_{abc}\, B^a \wedge B^b \wedge B^c\right)$$

$$\downarrow$$

$$\epsilon_{abc}\, B^a \wedge B^b \wedge B^c = \sqrt{g}\,\tilde{\lambda}\,\epsilon_{ijk}\, B^i \wedge B^j \wedge B^k + O(g) \qquad \tilde{\lambda} = 3\lambda/\sqrt{2}$$

$$\downarrow$$

$$B_{YM} = \gamma\, B_{GR} \qquad \gamma^3 = 3G^2\sqrt{g/2}$$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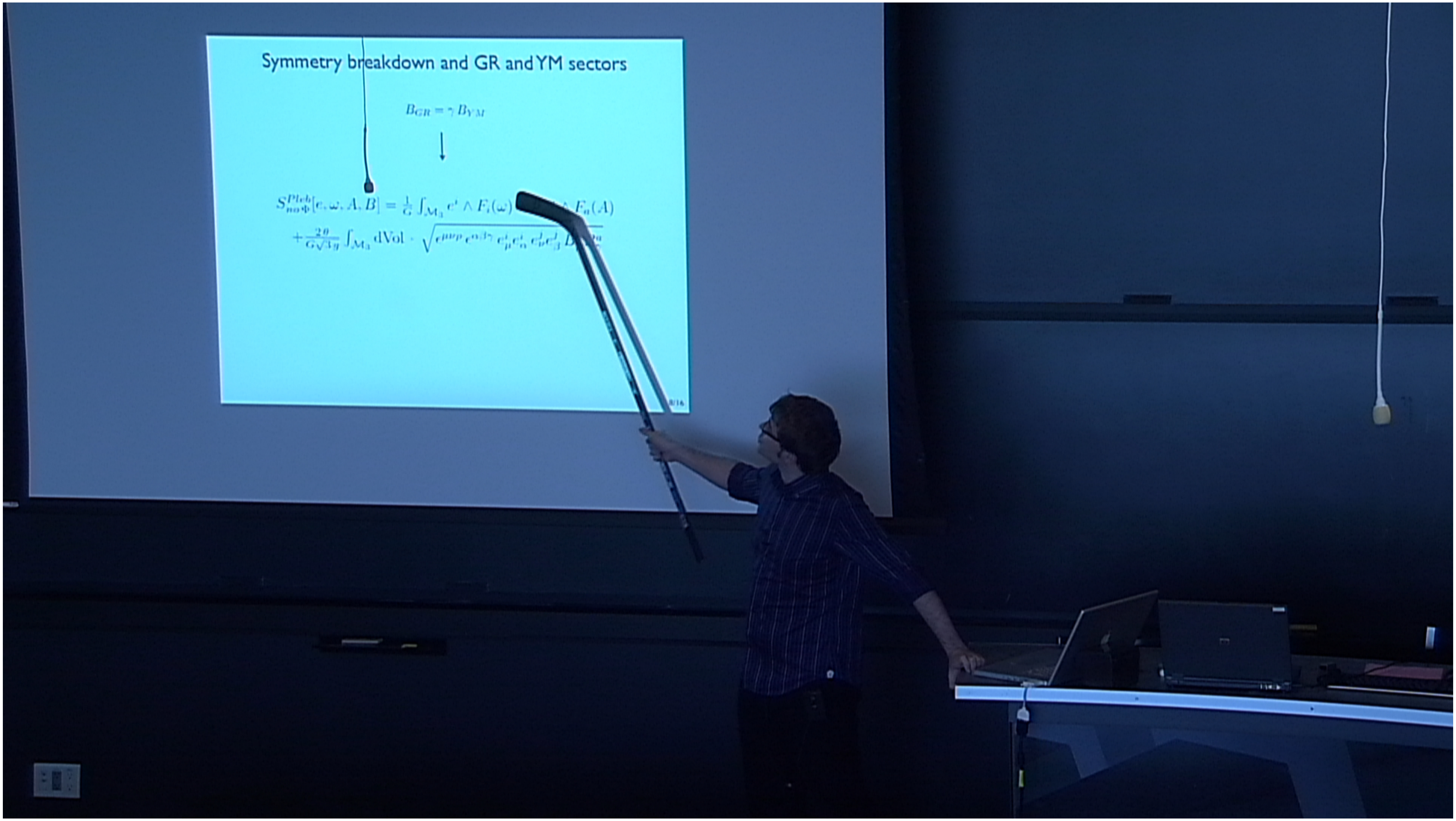
$B_{GR} = \gamma B_{YM}$
$S^{Pleb}_{no\Phi}[e, \omega, A, B] = \frac{1}{G}\int_{\mathcal{M}_3} e^i \wedge F_i(\omega) + B^a \wedge F_a(A)$
$+ \frac{2\theta}{G\sqrt{3g}} \int_{\mathcal{M}_3} \mathrm{dVol} \cdot \sqrt{\epsilon^{\mu\nu\rho}\epsilon^{\alpha\beta\gamma} e^i_\mu e^i_\alpha e^j_\nu e^j_\beta B^a_\rho B^a_\gamma}$
8/16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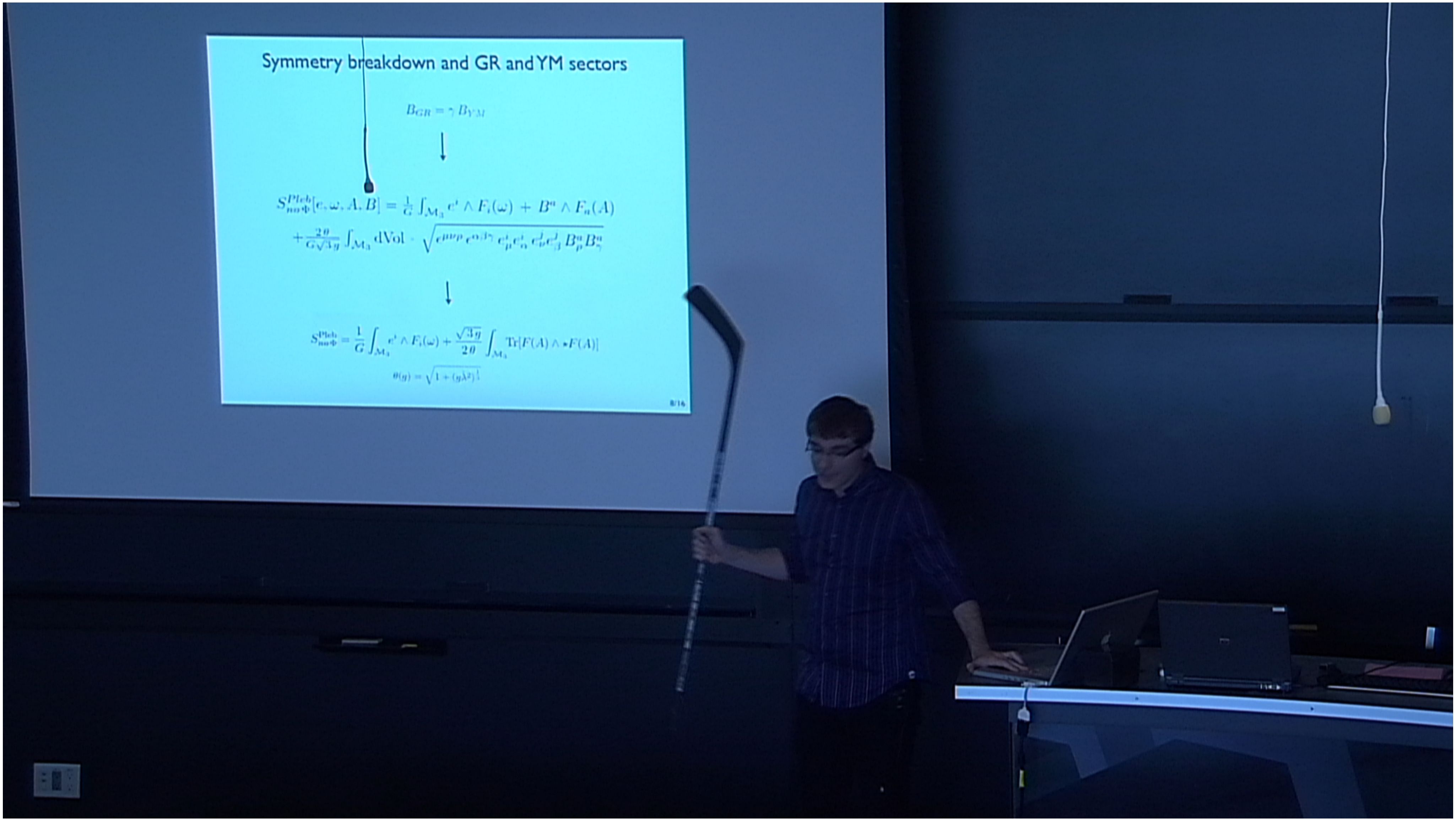
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$\theta(g) = \sqrt{1 + (g\lambda^2)^{\frac{1}{3}}}$
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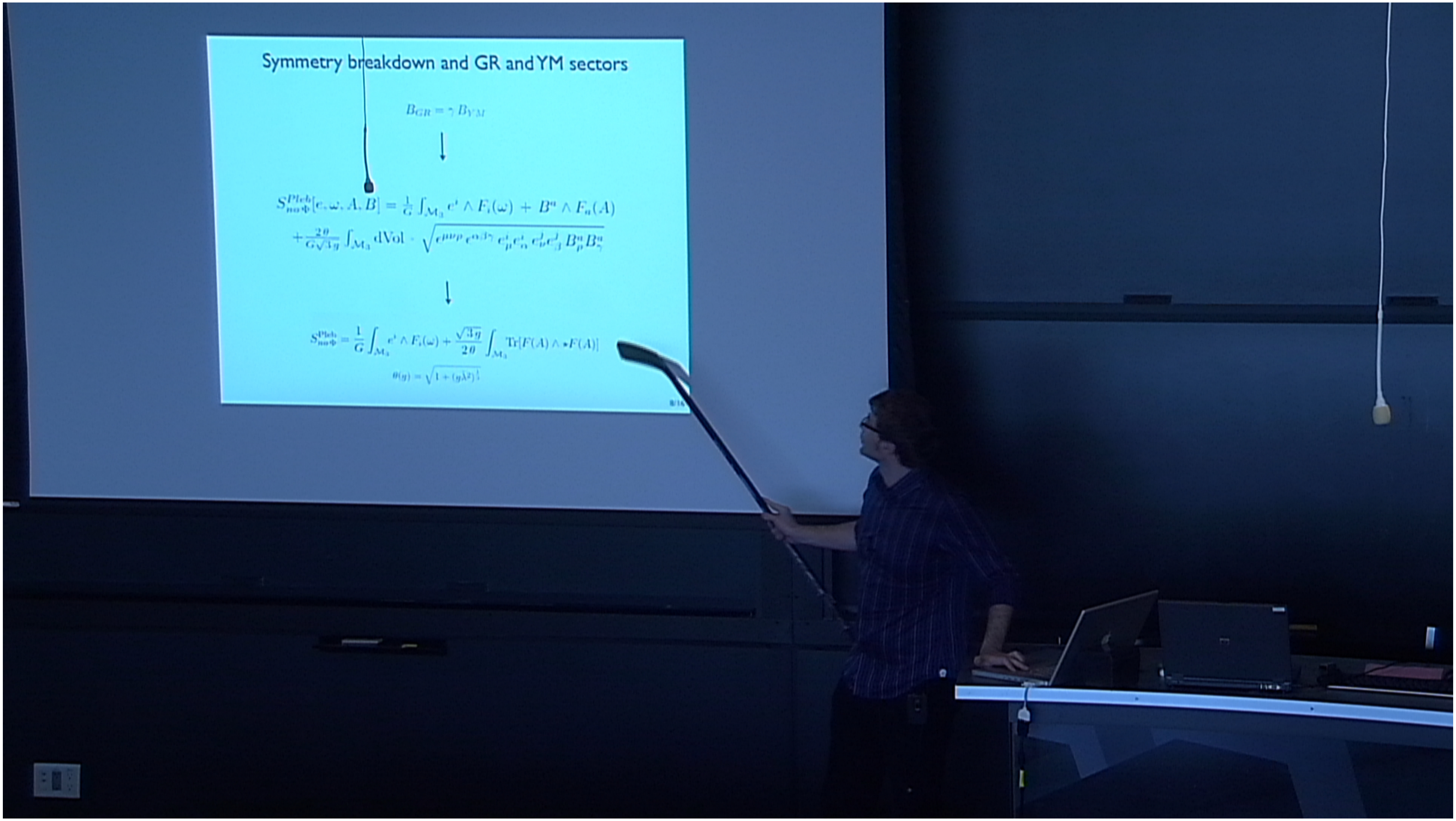
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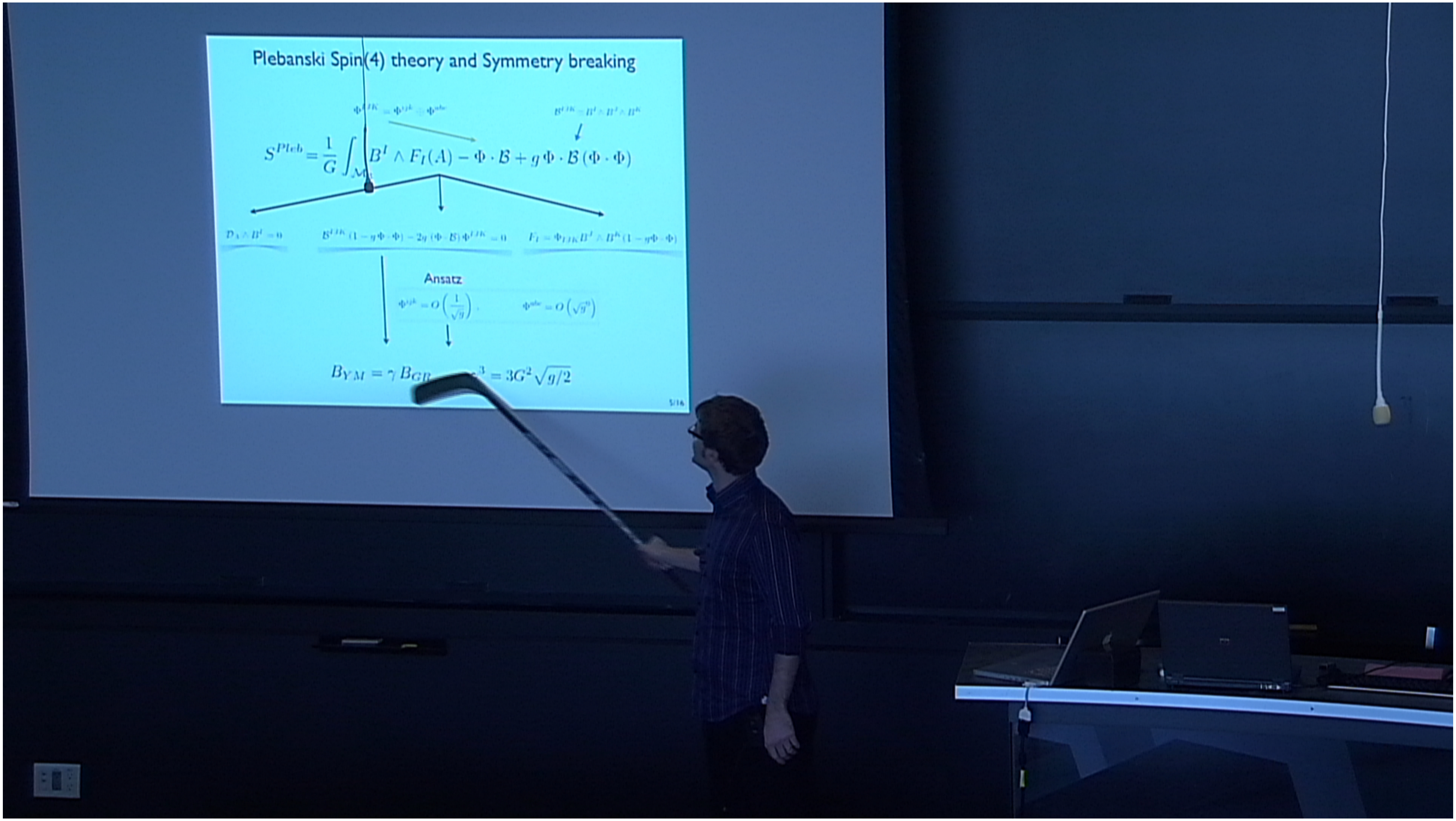
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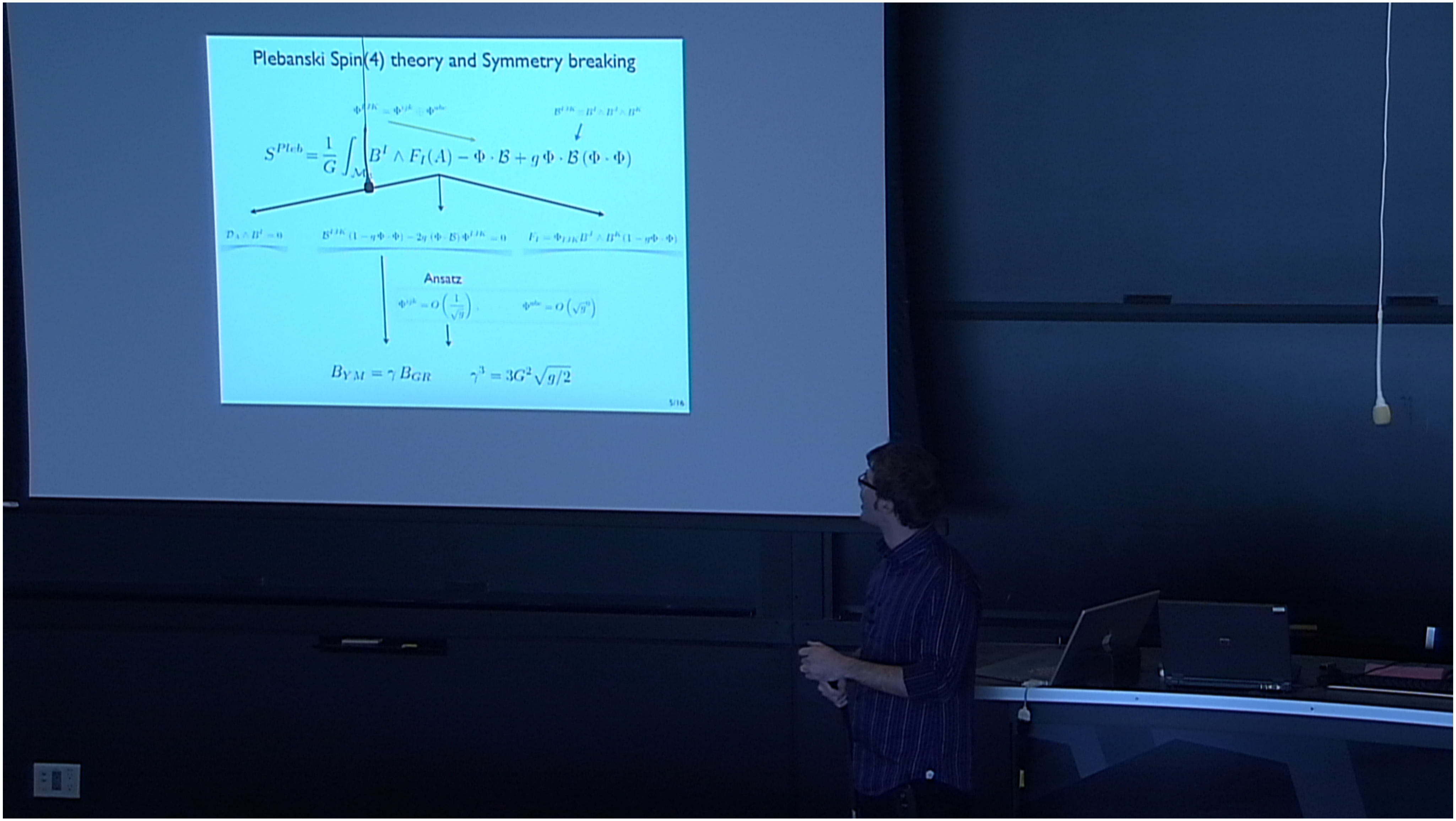
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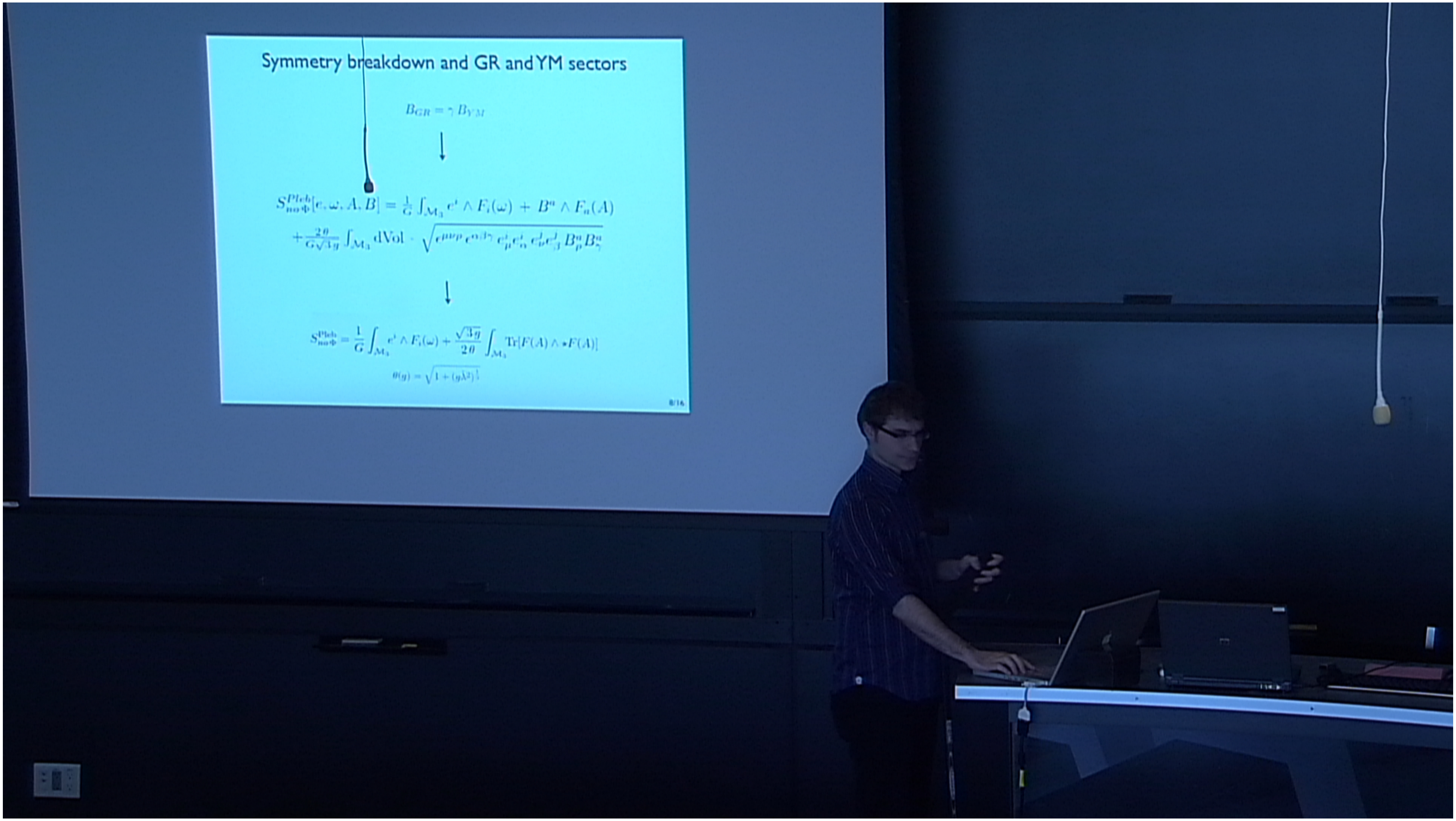
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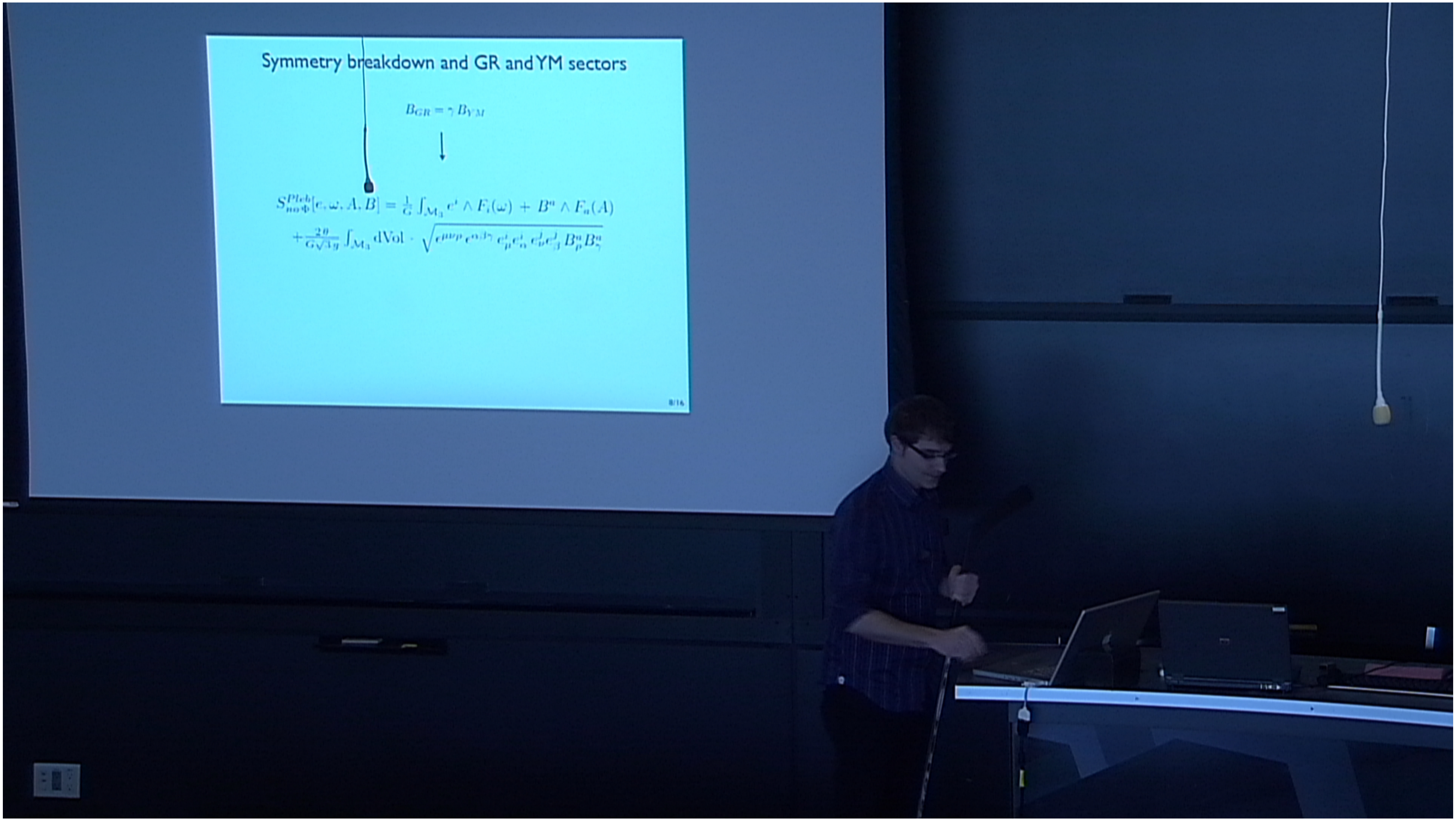
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$S^{Pleb}_{no\Phi}[e,\omega,A,B] = \frac{1}{G}\int_{\mathcal{M}_3} e^i \wedge F_i(\omega) + B^a \wedge F_a(A)$
$+\frac{2\theta}{G\sqrt{3g}}\int_{\mathcal{M}_3} \mathrm{dVol} \cdot \sqrt{\epsilon^{\mu\nu\rho}\epsilon^{\alpha\beta\gamma}\, e^i_\mu e^i_\alpha\, e^j_\nu e^j_\beta\, B^a_\rho B^a_\gamma}$
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Symmetry breakdown and GR and YM sectors
$B_{YM} = \gamma(g)\, B_{GR}$
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Symmetry breakdown and GR and YM sectors

$$\Phi^{LMN} = \frac{1}{\sqrt{3g}} \frac{B^L \wedge B^M \wedge B^N}{||B \wedge B \wedge B||}$$

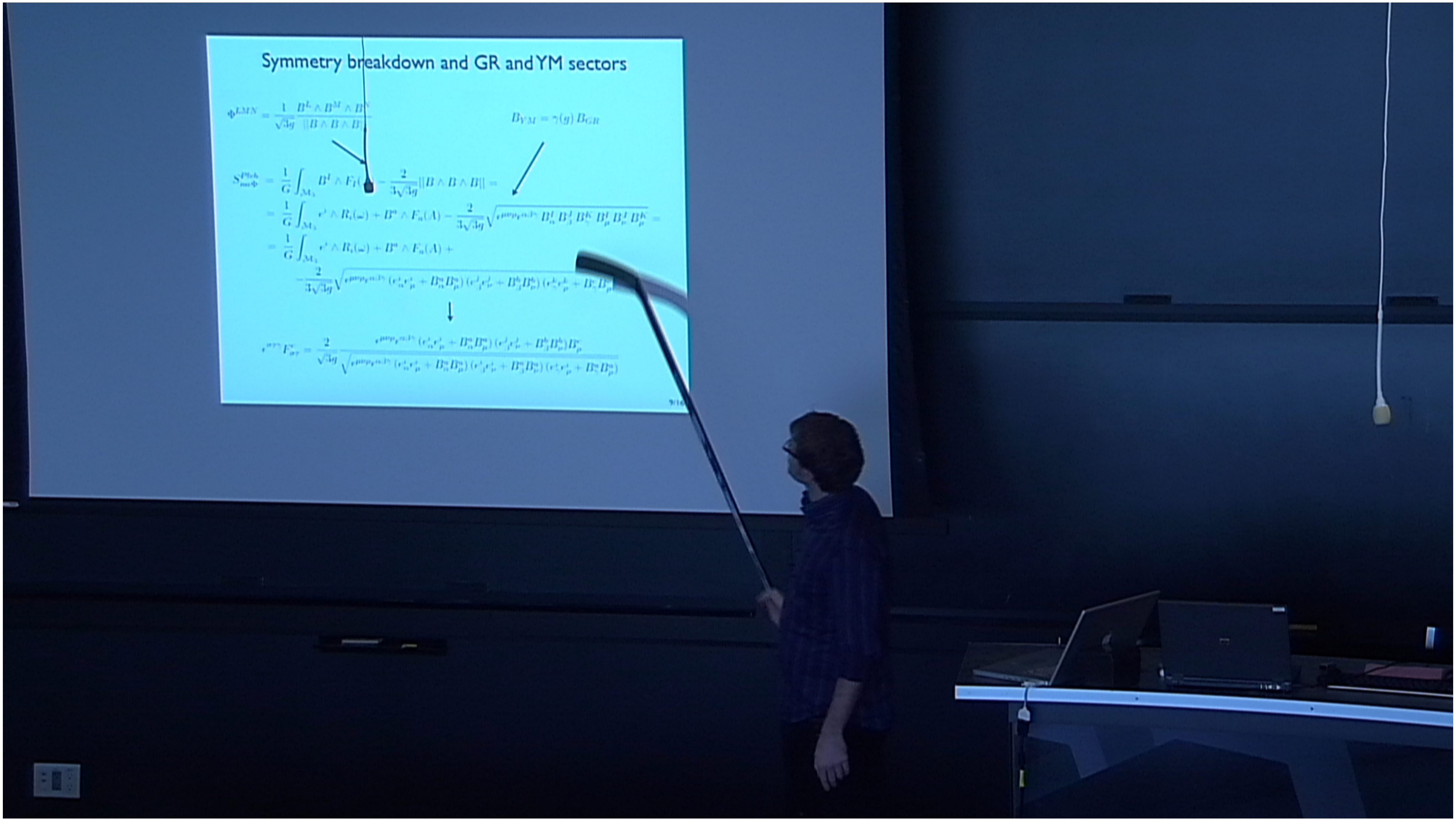
$$B_{YM} = \gamma(g)\, B_{GR}$$

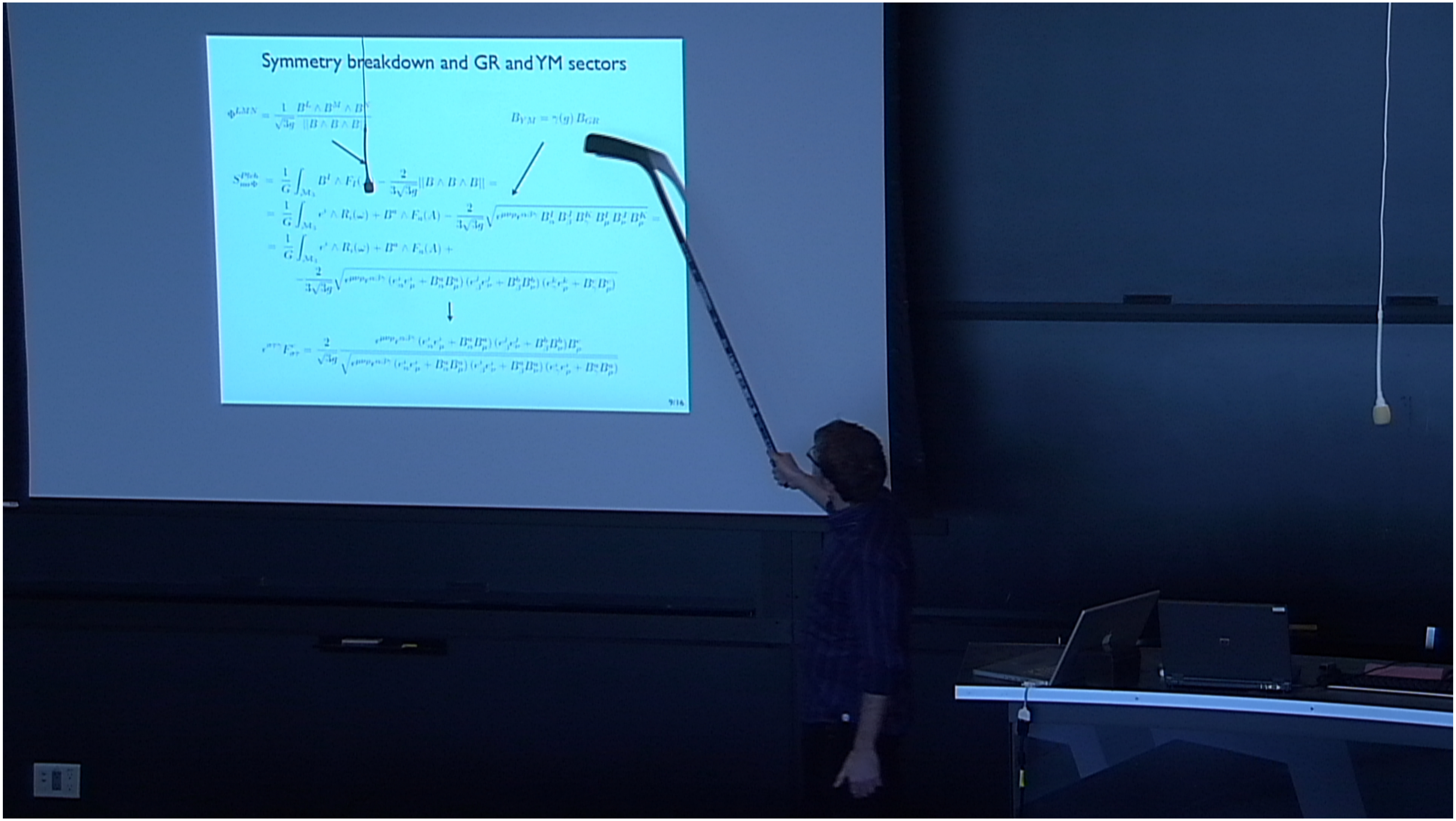
$$\begin{aligned}
S^{Pleb}_{no\,\Phi} &= \frac{1}{G}\int_{\mathcal{M}_3} B^I \wedge F_I(A) - \frac{2}{3\sqrt{3g}}||B \wedge B \wedge B|| = \\
&= \frac{1}{G}\int_{\mathcal{M}_3} e^i \wedge R_i(\omega) + B^a \wedge F_a(A) - \frac{2}{3\sqrt{3g}}\sqrt{\epsilon^{\mu\nu\rho}\epsilon^{\alpha\beta\gamma}\, B^I_\alpha\, B^J_\beta\, B^K_\gamma\, B^I_\mu\, B^J_\nu\, B^K_\rho} = \\
&= \frac{1}{G}\int_{\mathcal{M}_3} e^i \wedge R_i(\omega) + B^a \wedge F_a(A) + \\
&\quad - \frac{2}{3\sqrt{3g}}\sqrt{\epsilon^{\mu\nu\rho}\epsilon^{\alpha\beta\gamma}\,(e^i_\alpha e^i_\mu + B^a_\alpha B^a_\mu)\,(e^j_\beta e^j_\nu + B^b_\beta B^b_\nu)\,(e^k_\gamma e^k_\rho + B^c_\gamma B^c_\rho)}
\end{aligned}$$

↓

$$\epsilon^{\sigma\tau\gamma} F^c_{\sigma\tau} = \frac{2}{\sqrt{3g}} \frac{\epsilon^{\mu\nu\rho}\epsilon^{\alpha\beta\gamma}\,(e^i_\alpha e^i_\mu + B^a_\alpha B^a_\mu)\,(e^j_\beta e^j_\nu + B^b_\beta B^b_\nu) B^c_\rho}{\sqrt{\epsilon^{\mu\nu\rho}\epsilon^{\alpha\beta\gamma}\,(e^i_\alpha e^i_\mu + B^a_\alpha B^a_\mu)\,(e^i_\beta e^i_\nu + B^a_\beta B^a_\nu)\,(e^i_\gamma e^i_\rho + B^a_\gamma B^a_\rho)}}$$

9/16


Symmetry breakdown and GR and YM sectors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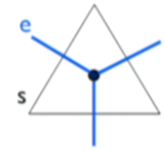
9/16

LQG and spin foam quantization

Introduce an oriented triangulation Δ
over the manifold $\mathcal{M}_3$ and its dual Δ^*



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$$\begin{aligned} S^{Pleb}_{no\,\Phi} &= \frac{1}{G} \int_{\mathcal{M}_3} B^I \wedge F_I(A) - \frac{2}{3\sqrt{3g}} ||B \wedge B \wedge B|| = \\ &= \frac{1}{G} \int_{\mathcal{M}_3} e^i \wedge R_i(\omega) + B^a \wedge F_a(A) - \frac{2}{3\sqrt{3g}} \sqrt{\epsilon^{\mu\nu\rho} \epsilon^{\alpha\beta\gamma}\, B^I_\alpha\, B^J_\beta\, B^K_\gamma\, B^I_\mu\, B^J_\nu\, B^K_\rho} = \\ &= \frac{1}{G} \int_{\mathcal{M}_3} e^i \wedge R_i(\omega) + B^a \wedge F_a(A) + \\ &\quad - \frac{2}{3\sqrt{3g}} \sqrt{\epsilon^{\mu\nu\rho} \epsilon^{\alpha\beta\gamma} \left(e^i_\alpha e^i_\mu + B^a_\alpha B^a_\mu\right) \left(e^j_\beta e^j_\nu + B^b_\beta B^b_\nu\right) \left(e^k_\gamma e^k_\rho + B^c_\gamma B^c_\rho\right)} \end{aligned}$$

↓

$$\epsilon^{\sigma\tau\gamma} F^c_{\sigma\tau} = \frac{2}{\sqrt{3g}} \frac{\epsilon^{\mu\nu\rho} \epsilon^{\alpha\beta\gamma} \left(e^i_\alpha e^i_\mu + B^a_\alpha B^a_\mu\right) \left(e^j_\beta e^j_\nu + B^b_\beta B^b_\nu\right) B^c_\rho}{\sqrt{\epsilon^{\mu\nu\rho} \epsilon^{\alpha\beta\gamma} \left(e^i_\alpha e^i_\mu + B^a_\alpha B^a_\mu\right) \left(e^i_\beta e^i_\nu + B^a_\beta B^a_\nu\right) \left(e^i_\gamma e^i_\rho + B^a_\gamma B^a_\rho\right)}}$$

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LQG and spin foam quantization

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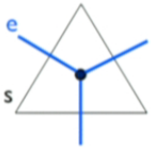

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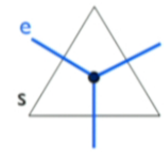

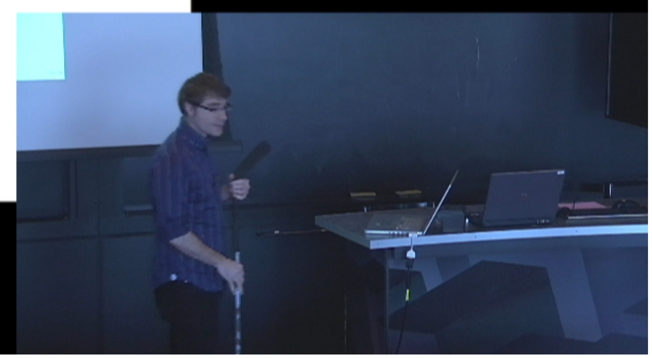

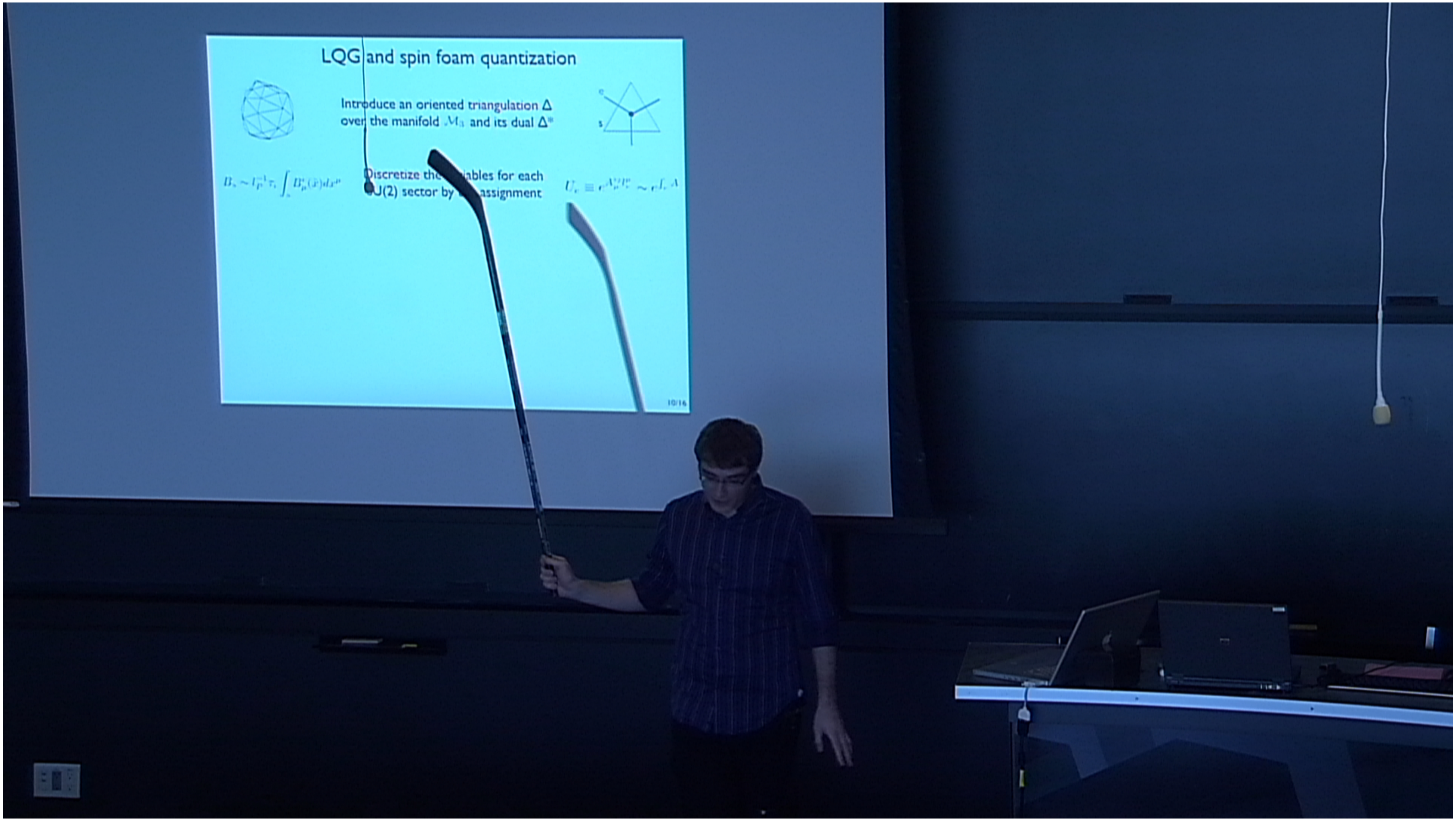
LQG and spin foam quantization
Introduce an oriented triangulation Δ
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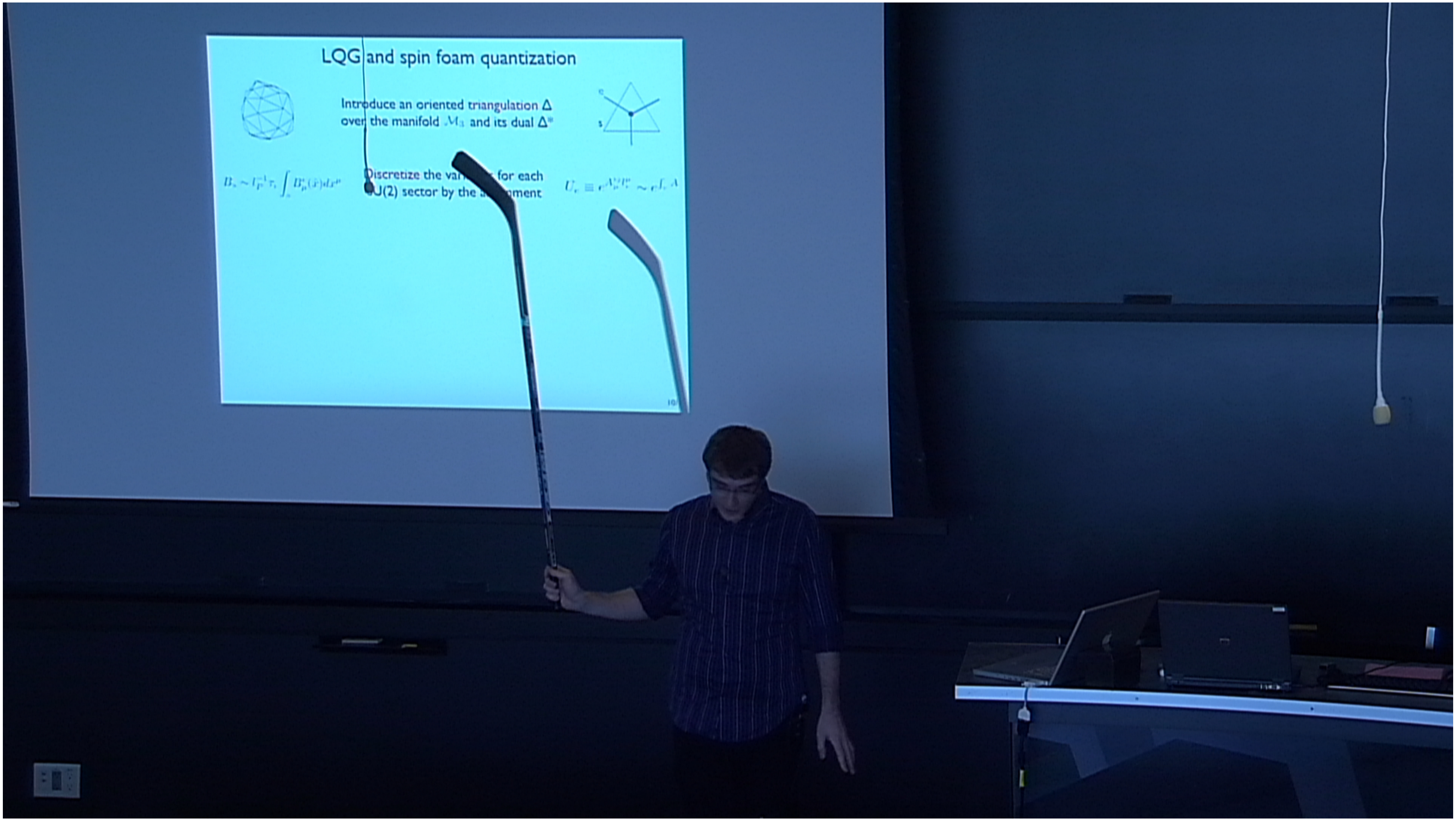
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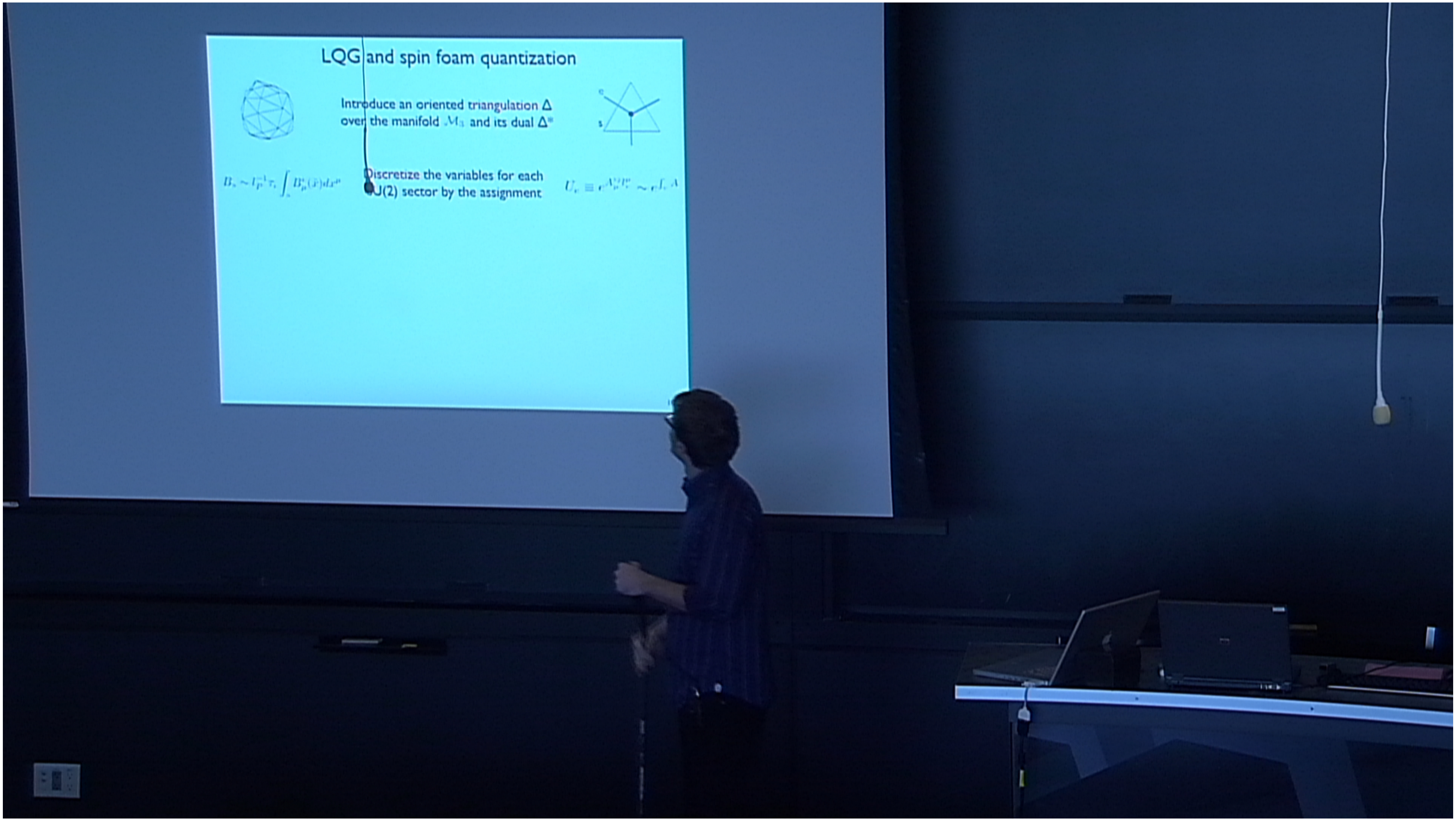
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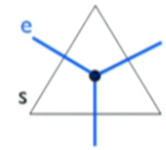


$B_s \sim l_P^{-1} \tau_i \int_s B^i_\mu(\tilde{x}) dx^\mu$

Discretize the variables for each
SU(2) sector by the assignment

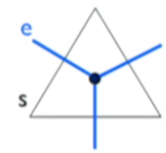
$U_e \equiv e^{A^{ij}_\mu l^\mu_e} \sim e^{\int_e A}$

Loop quantize the SU(2)-cotangent space over $\Sigma \subset \mathcal{M}_3$
construct the Hilbert space of cylindrical functions $\mathcal{H}_{\mathrm{Cyl}}$
represent as multiplicative holonomies and as LI derivatives fluxes

10/16

LQG and spin foam quantization

Introduce an oriented triangulation Δ over the manifold $\mathcal{M}_3$ and its dual Δ^*



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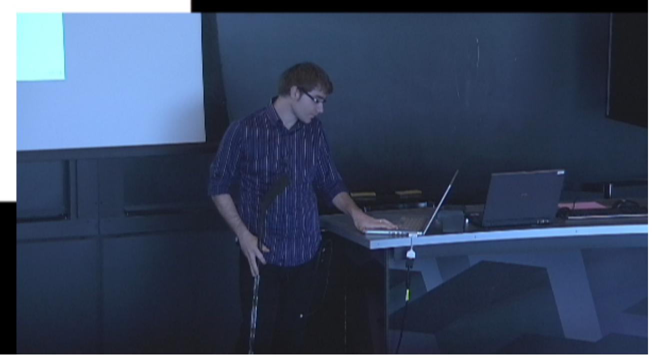
Spin-Networks and reduction of the quantized kinematical Hilbert space



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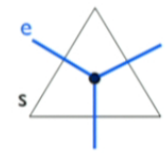

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Spin foam techniques realize the implementation of the scalar constraint

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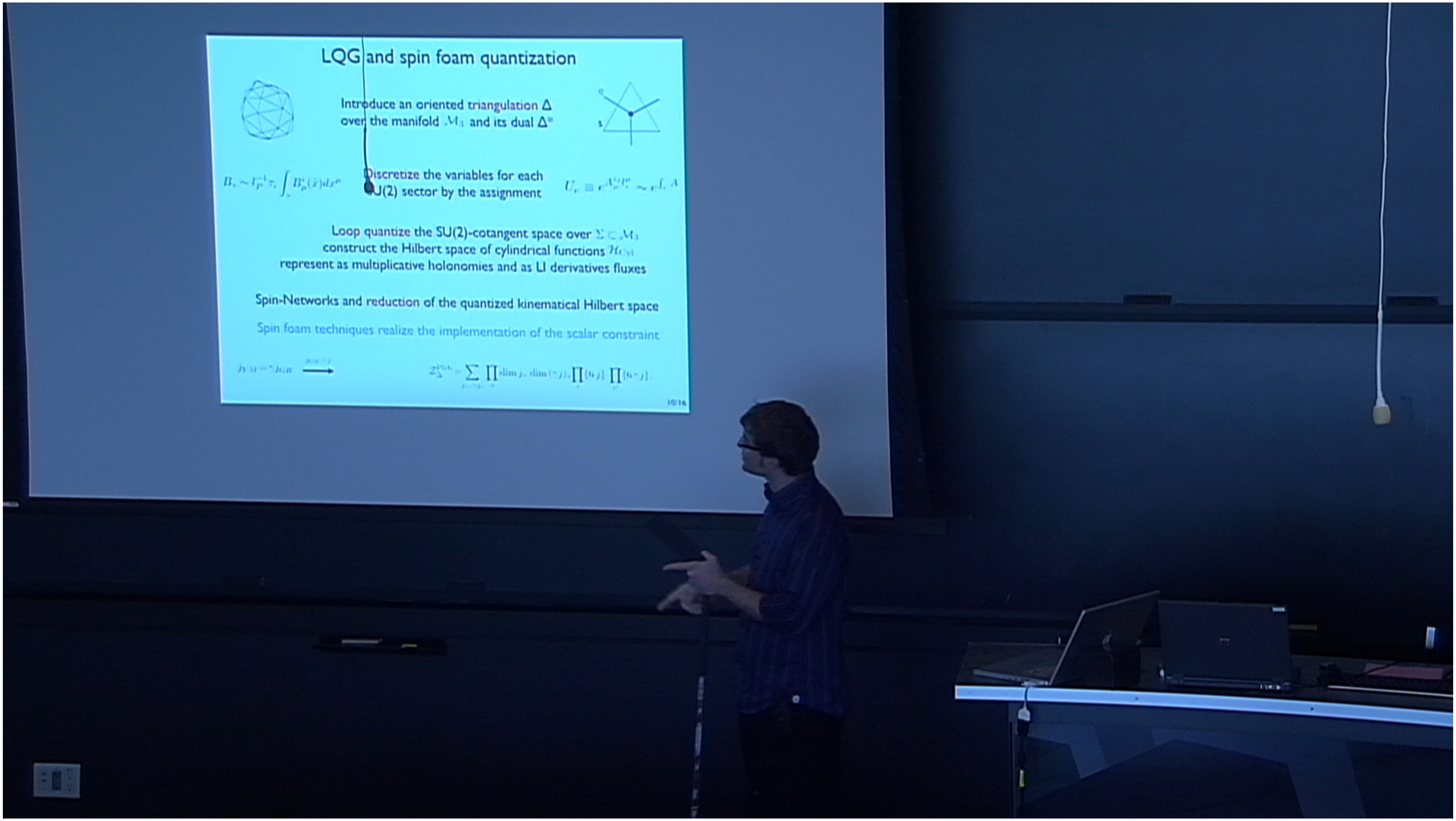
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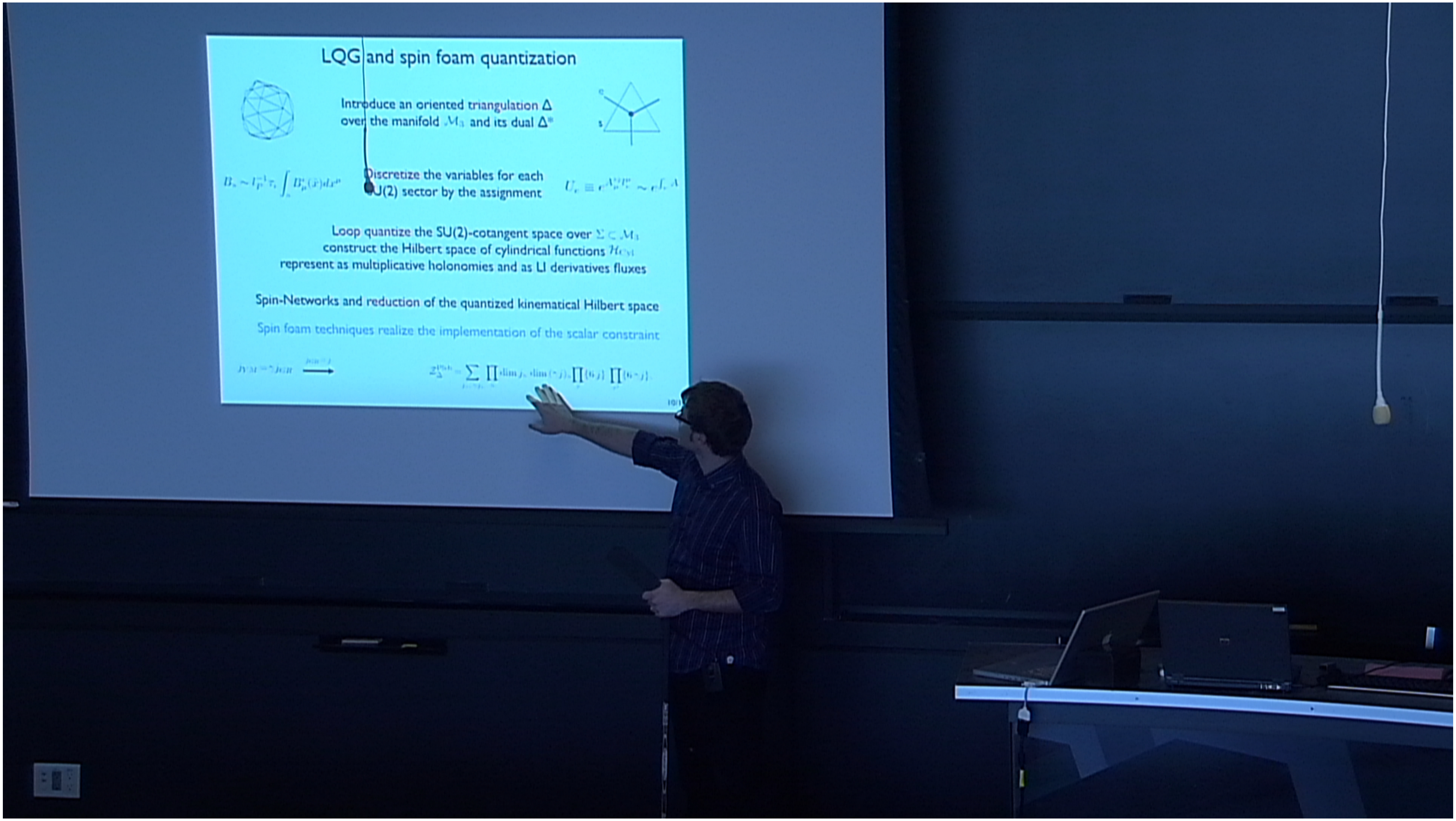
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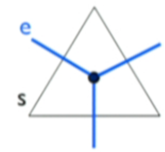

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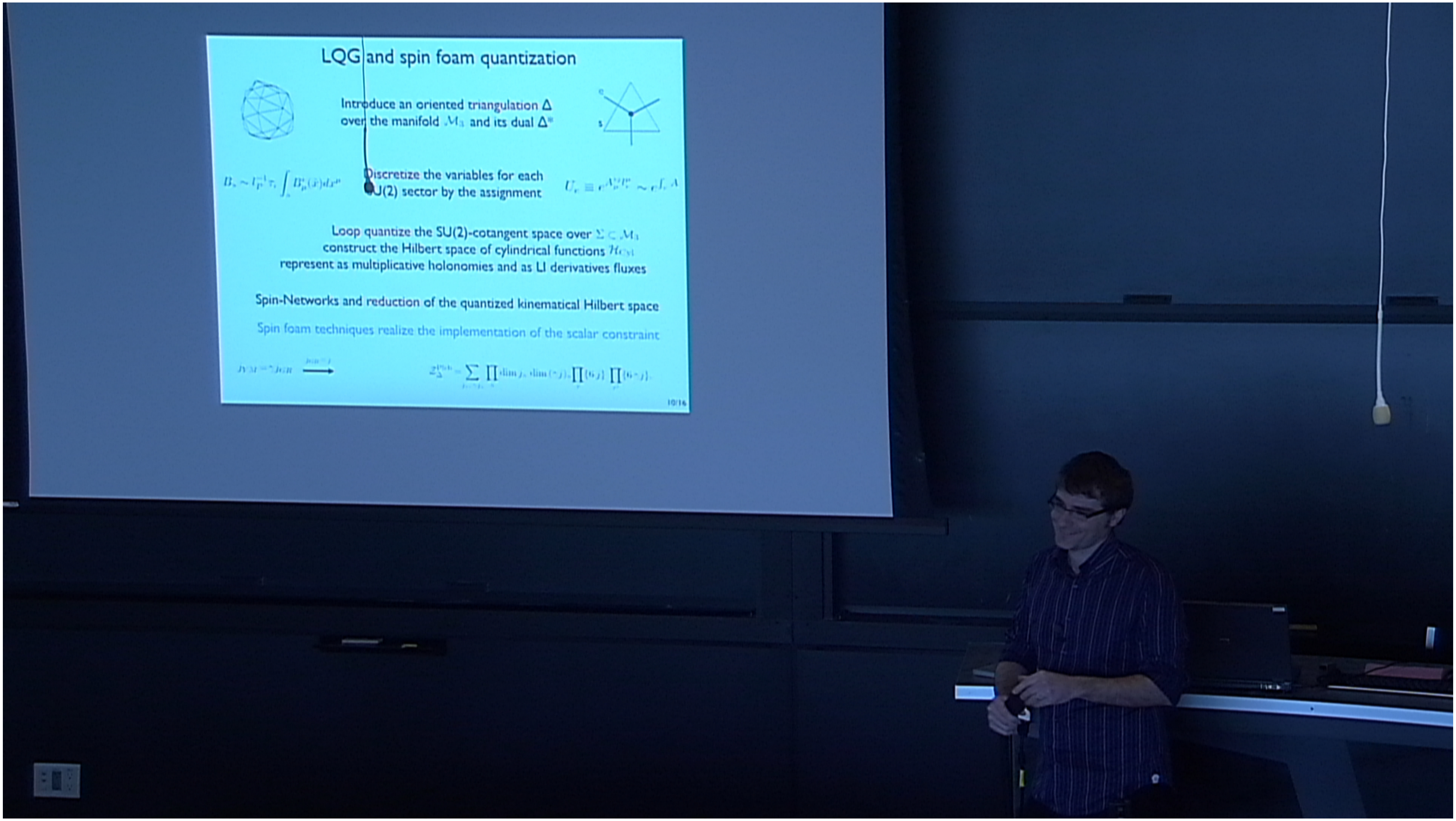
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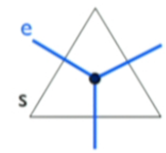

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$$\mathcal{K}_t(G) = \sum_{j,\gamma j} \dim j \dim(\gamma j)\, e^{-j(j+1)\frac{t}{2}} \mathrm{Tr}\left[\Pi^{(j,\gamma j)}(\tilde{G}_n G \tilde{G}^{-1}_{n'})\right]$$

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LQG and spin foam quantization

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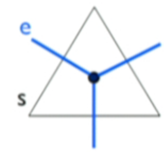

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Coherent states for GR and YM sectors

$$H_l = n_{s(l)} e^{-iz_l \frac{\sigma_3}{2}} n_{t(l)}^{-1}$$
$$\mathbb{H} = H \times H' \in \mathrm{SL}(2,\mathbb{C}) \otimes \mathrm{SL}(2,\mathbb{C})$$

$\longrightarrow$

$$\Psi_{\Gamma,\mathbb{H}_l}(G_l) = \int_{\mathrm{Spin}(4)^4} \left(\prod_n d\tilde{G}_n\right) \prod_l \mathcal{K}_{t_l}\left(G_l, \tilde{G}_n \mathbb{H}_l \tilde{G}_n^{-1}\right)$$

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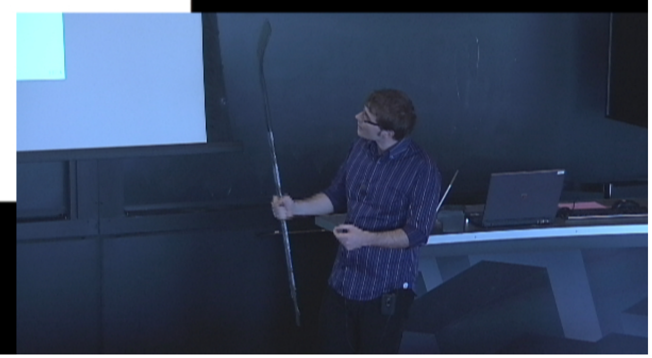

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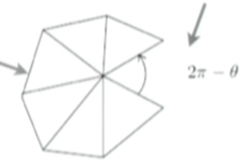
$$\Psi^{GR+YM}_{\Gamma,\mathbb{H}_l}(G_l) \equiv \Psi^{GR}_{\Gamma,H_l}(h_l)\, \Psi^{YM}_{\Gamma,H'_l}(h_{l'}) = \sum_{j_l,\iota} \sum_{\gamma j_l,\iota^\gamma} \left(\prod_l \dim j_l\, e^{-\frac{(j_l - j_l^0)^2}{2\sigma_l^2}} e^{-i\xi_l j_l} \cdot \prod_n \Phi_{\iota_n}(n_l)\right) \times$$
$$\left(\prod_l \dim \gamma j_l\, e^{-\frac{(\gamma j_l - \gamma j_l^0)^2}{2\sigma_l^2}} e^{-i\xi_l^\gamma \gamma j_l} \cdot \prod_n \Phi_{\iota_n^\gamma}(n_l)\right) \Psi_{\Gamma,j_l,\iota_n}(h_l)\, \Psi_{\Gamma,\gamma j_l,\iota_n^\gamma}(h'_l)$$

$$\gamma^{-1} j_l^0 = l_p^{-1} \int_s B^a_\mu dx^\mu \tau_a \qquad \xi_\gamma = \gamma^2 \xi$$

$$j_l^0 = l_p^{-1} \int_s e^i_\mu dx^\mu \tau_i \qquad \xi_l = \theta$$



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$$\Psi^{GR+YM}_{\Gamma,\mathbb{H}_l}(G_l) \equiv \Psi^{GR}_{\Gamma,H_l}(h_l)\, \Psi^{YM}_{\Gamma,H'_l}(h_{l'}) = \sum_{j_l,\iota} \sum_{\gamma j_l,\iota^\gamma} \left(\prod_l \dim j_l\, e^{-\frac{(j_l - j_l^0)^2}{2\sigma_l^2}} e^{-i\xi_l j_l} \cdot \prod_n \Phi_{\iota_n}(n_l) \right) \times$$
$$\left(\prod_l \dim \gamma j_l\, e^{-\frac{(\gamma j_l - \gamma j_l^0)^2}{2\sigma_l^2}} e^{-i\xi_l^\gamma \gamma j_l} \cdot \prod_n \Phi_{\iota_n^\gamma}(n_l) \right) \Psi_{\Gamma, j_l, \iota_n}(h_l)\, \Psi_{\Gamma, \gamma j_l, \iota_n^\gamma}(h'_l)$$

$$\gamma^{-1} j_l^0 = l_p^{-1} \int_s B^a_\mu dx^\mu \tau_a \qquad \xi_\gamma = \gamma^2 \xi$$

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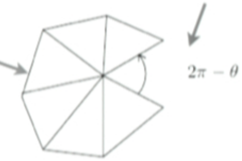

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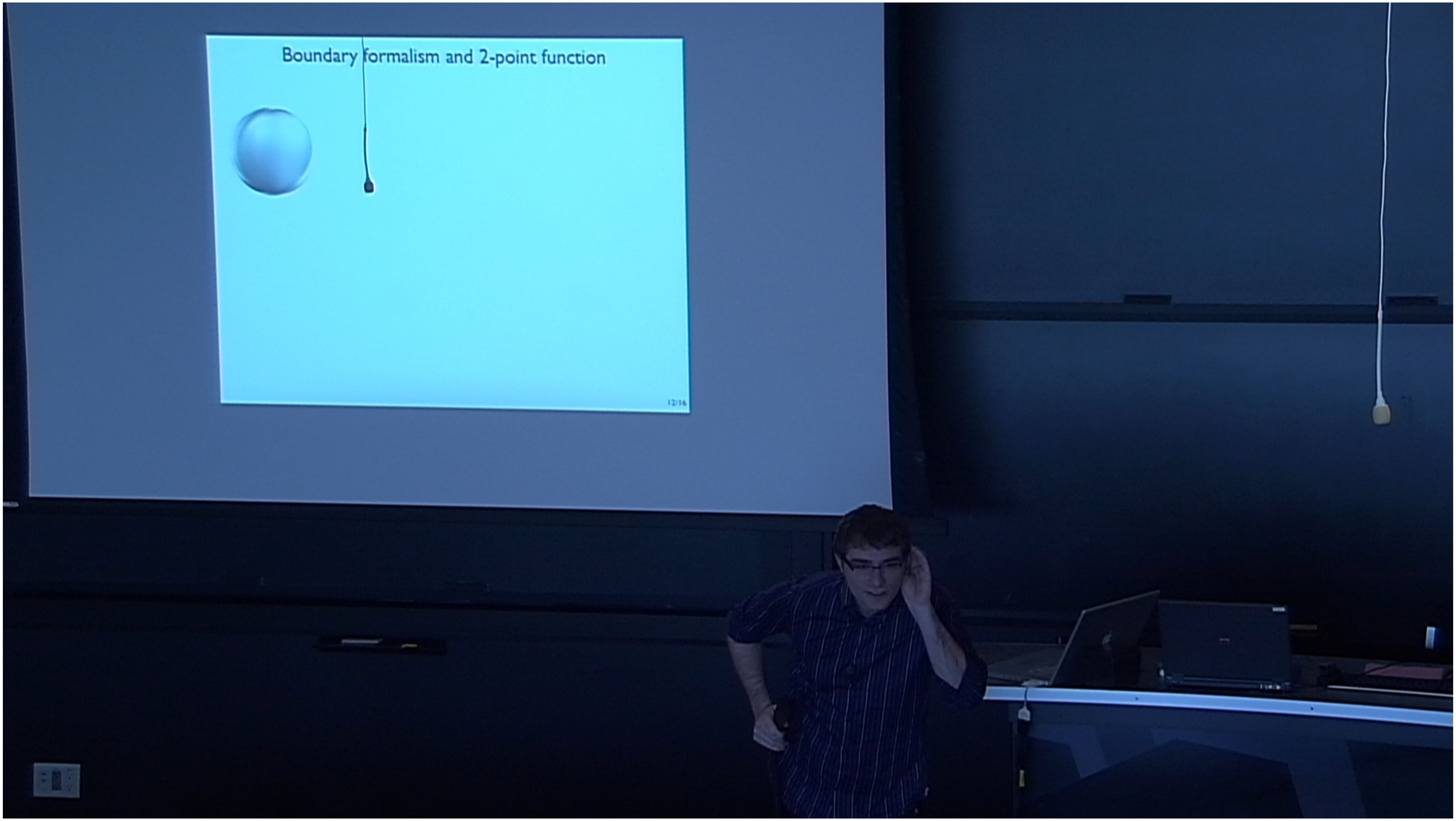
Boundary formalism and 2-point function
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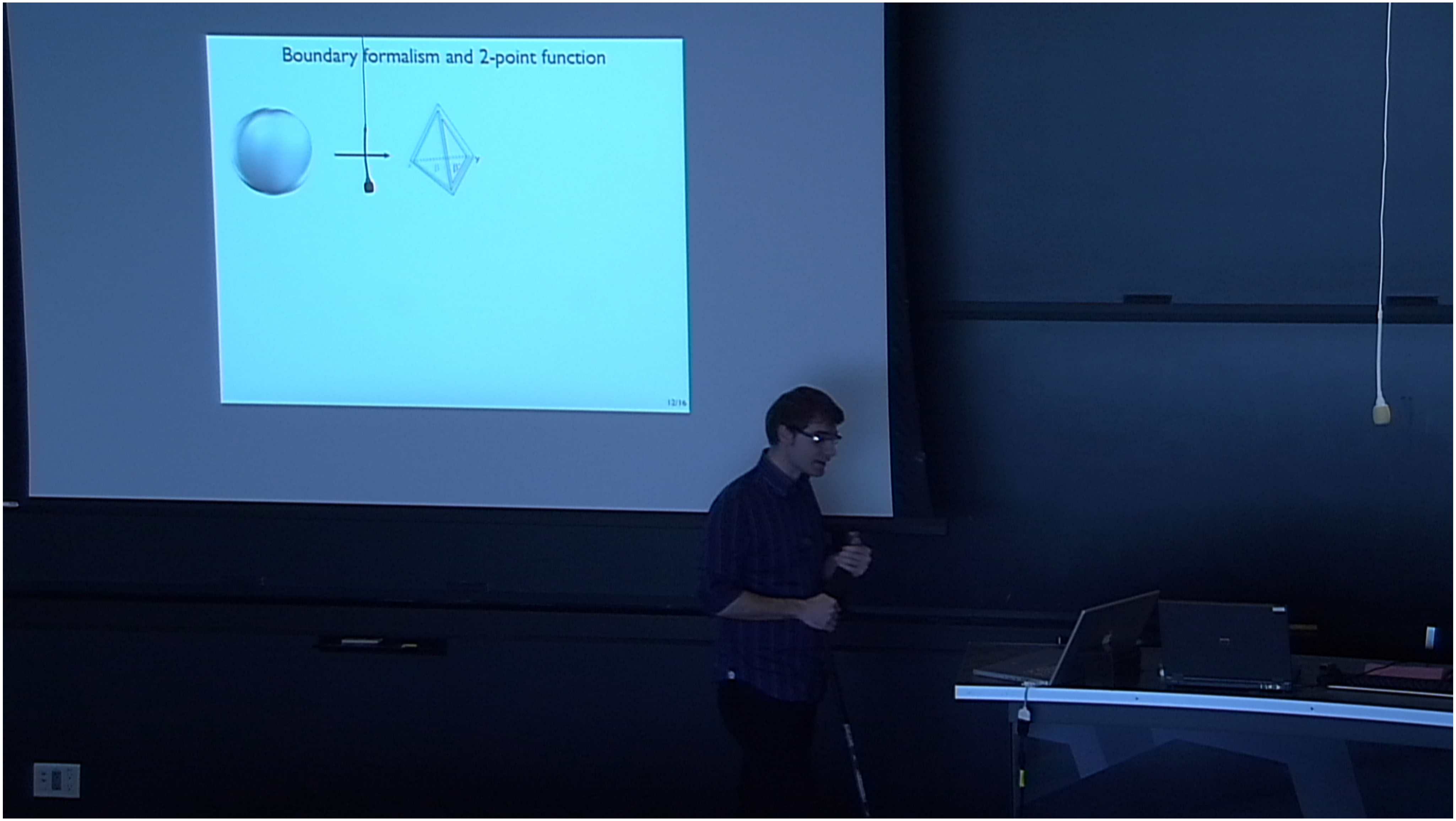
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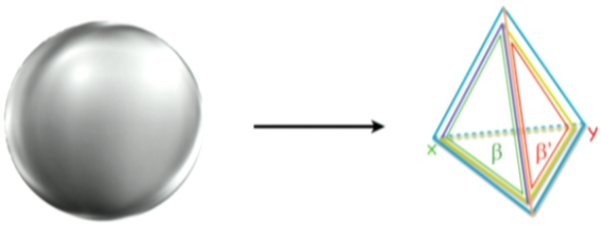
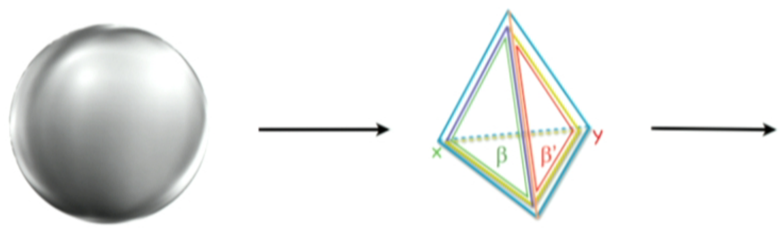
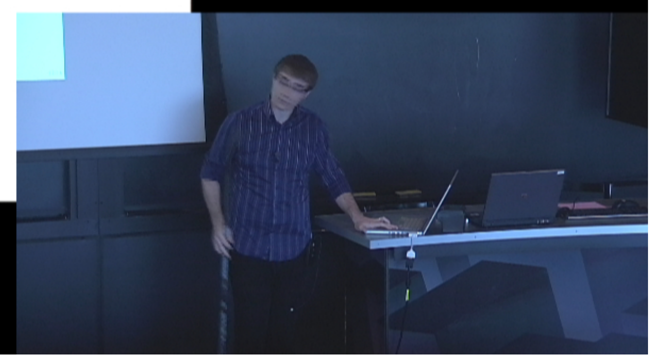
Boundary formalism and 2-point function



Boundary formalism and 2-point function

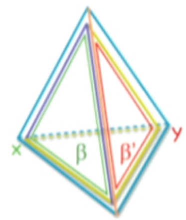


$$\langle A_{YM}(x)A_{GR}(y)\rangle$$



Boundary formalism and 2-point function

$\longrightarrow$



$\longrightarrow$ $\langle A_{YM}(x)A_{GR}(y)\rangle$

$\downarrow$

$$\mathcal{A} = \langle W_v(G_l)|U_{\beta_{\mathbf{x}}}(h_l)U_{\beta'_{\mathbf{y}}}(h'_l)|\Psi_{\Gamma,\mathbb{H}_l}(G_l)\rangle$$

$\downarrow$

$$\mathcal{A} = \sum_{j_l,\gamma j_l} \tilde{\mathcal{A}}(j_m, s_1)\prod_l \dim j_l \, e^{-\frac{(j_l-j_l^0)^2}{2\sigma_l^2}} e^{-i\xi_l j_l} \prod_n \Phi_\iota(n_l) \times$$

$$\tilde{\mathcal{A}}(\gamma j_n, s_1)\prod_{l'} \dim\gamma j_{l'} \, e^{-\frac{(\gamma j_{l'}-\gamma j_{l'}^0)^2}{2\sigma_{l'}^2}} e^{-i\xi_\gamma^{l'}\gamma j_{l'}} \prod_n \Phi_{\iota_\gamma}(n_{l'}).$$

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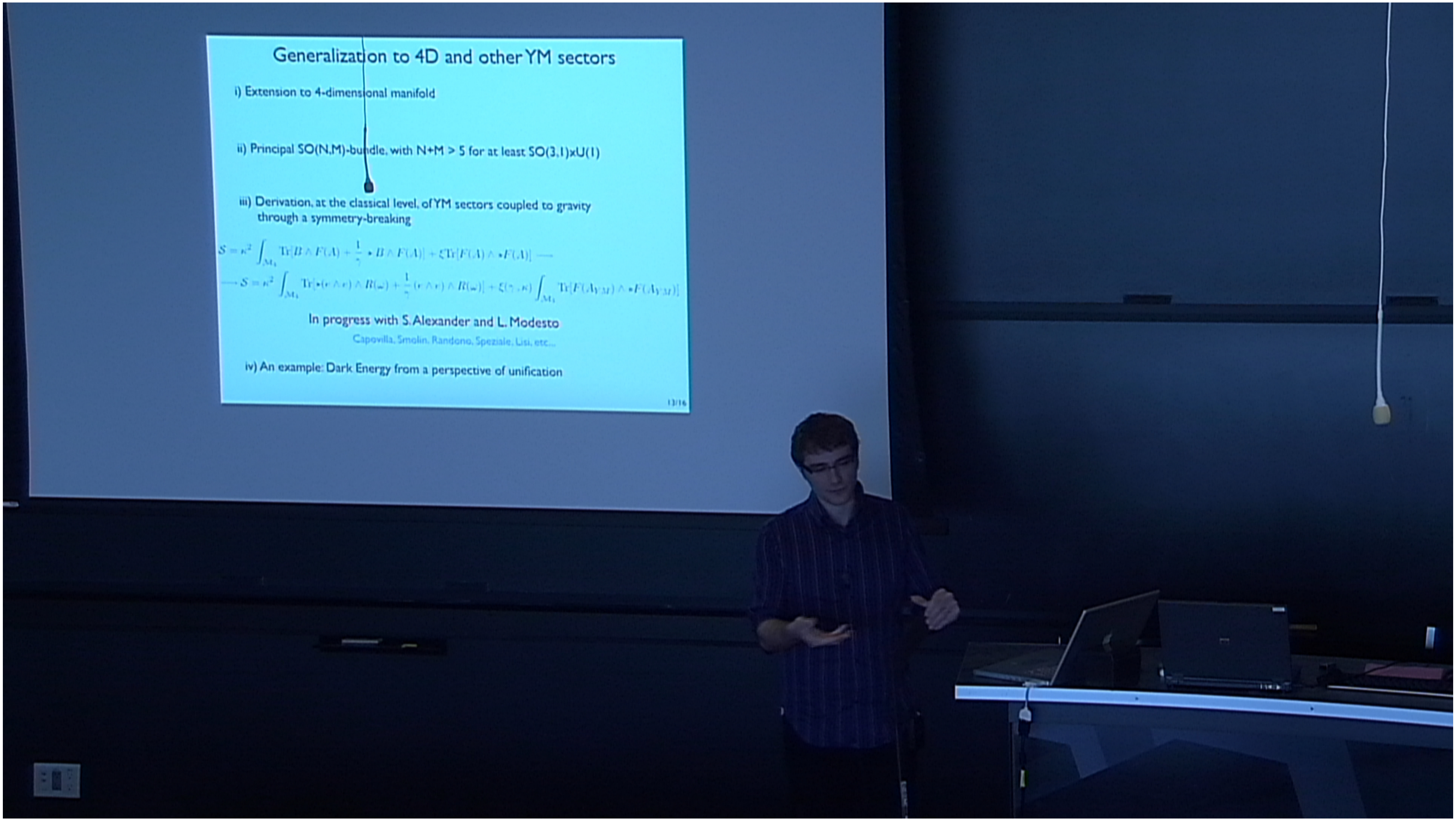
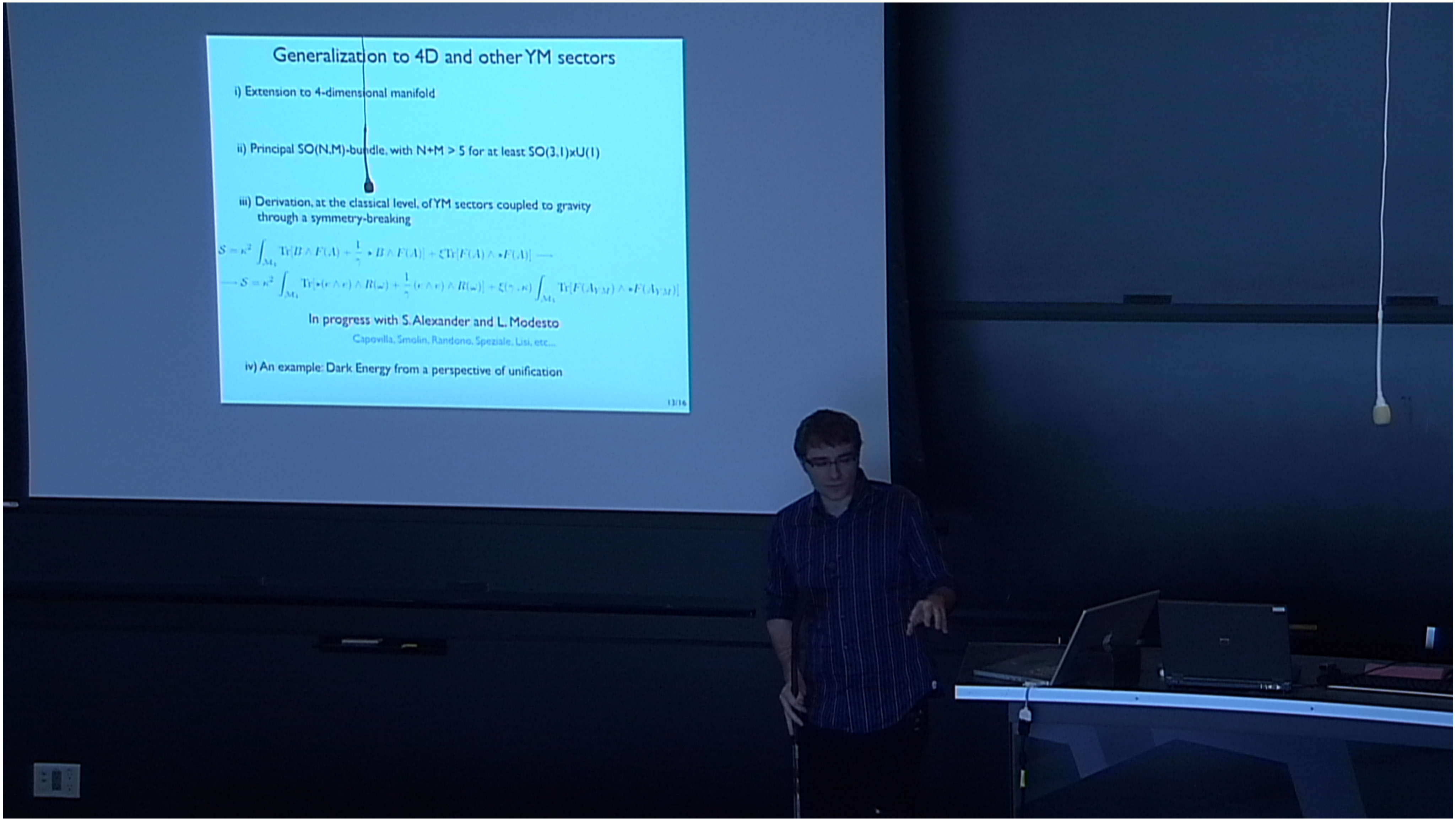

Generalization to 4D and other YM sectors
i) Extension to 4-dimensional manifold
ii) Principal SO(N,M)-bundle, with N+M > 5 for at least SO(3,1)xU(1)
iii) Derivation, at the classical level, of YM sectors coupled to gravity through a symmetry-breaking
$S = \kappa^2 \int_{M_4} \mathrm{Tr}[B \wedge F(A) + \frac{1}{\gamma} \star B \wedge F(A)] + \xi \mathrm{Tr}[F(A) \wedge \star F(A)] \longrightarrow$
$\longrightarrow S = \kappa^2 \int_{M_4} \mathrm{Tr}[\star(e \wedge e) \wedge R(\omega) + \frac{1}{\gamma} (e \wedge e) \wedge R(\omega)] + \xi(\gamma, \kappa) \int_{M_4} \mathrm{Tr}[F(A_{YM}) \wedge \star F(A_{YM})]$
In progress with S. Alexander and L. Modesto
Capovilla, Smolin, Randono, Speziale, Lisi, etc...
iv) An example: Dark Energy from a perspective of unification
13/16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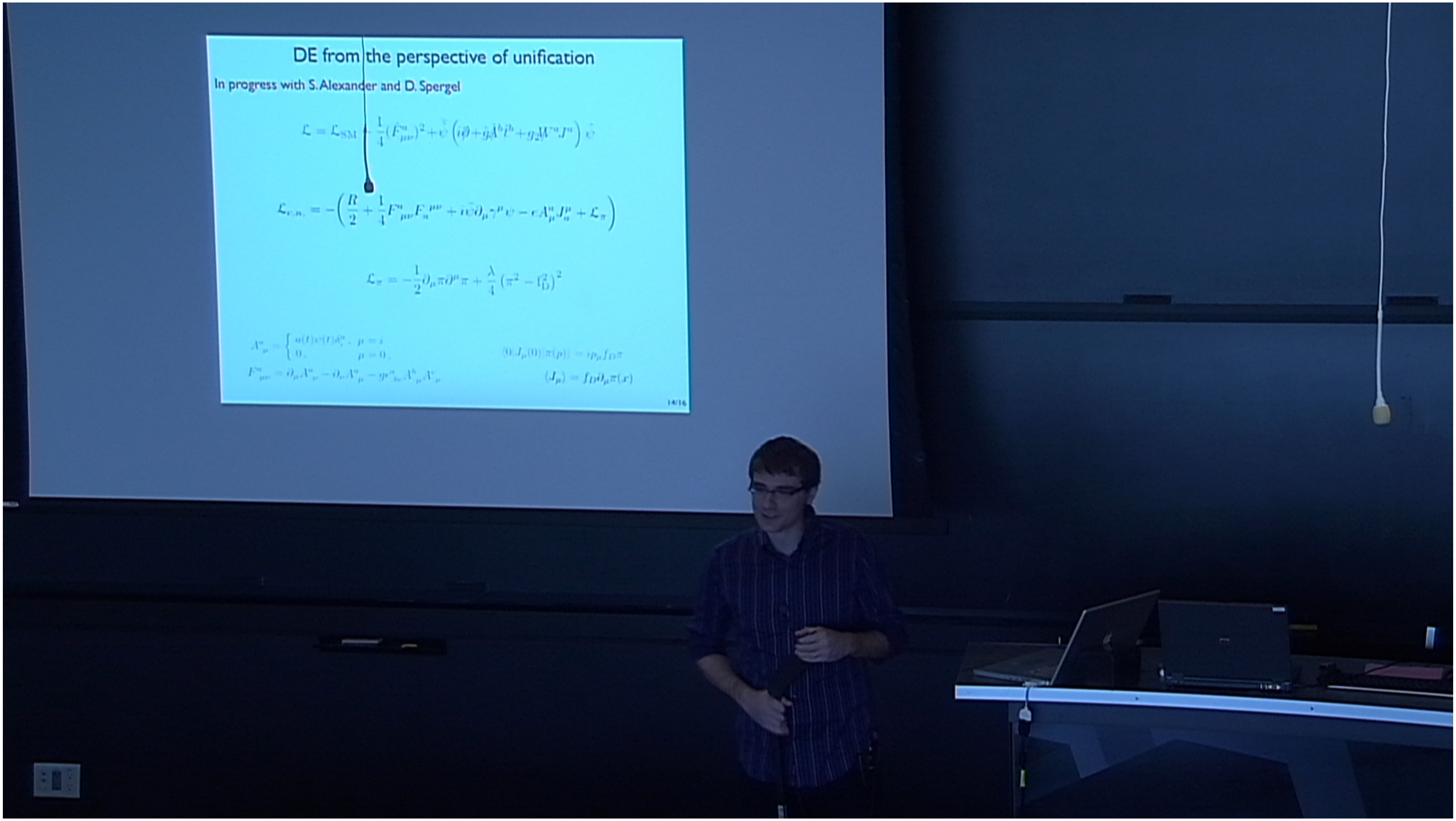
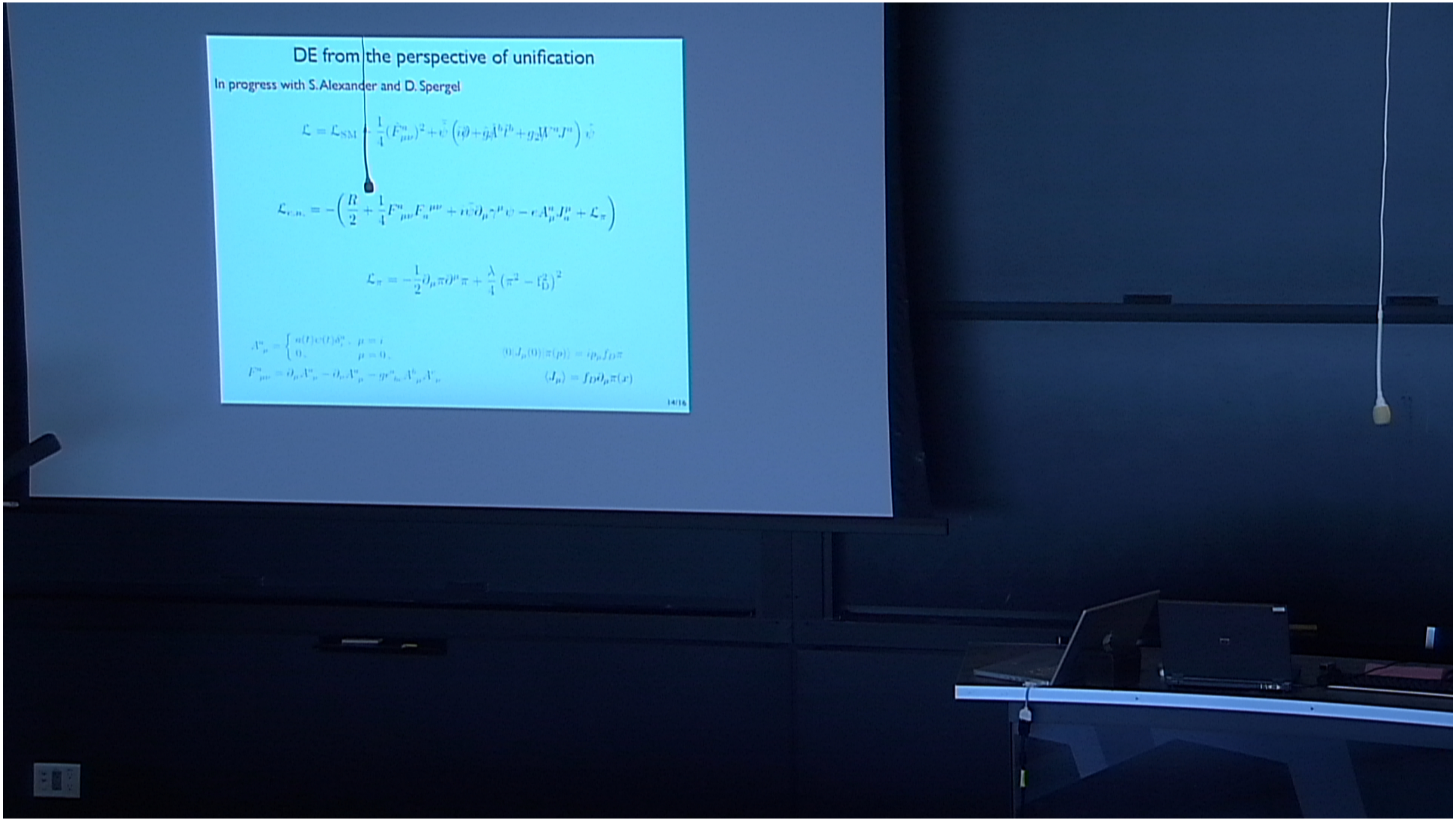

DE from the perspective of unification
In progress with S. Alexander and D. Spergel
$\mathcal{L}_\pi = -\frac{1}{2}\partial_\mu \pi \partial^\mu \pi + \frac{\lambda}{4}\left(\pi^2 - f_D^2\right)^2$
$\langle 0|J_\mu(0)|\pi(p)\rangle = i p_\mu f_D \pi$
$\langle J_\mu \rangle = f_D \partial_\mu \pi(x)$
14/16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DE from the perspective of unification

In progress with S. Alexander and D. Spergel

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} - \frac{1}{4}(\hat{F}^a_{\mu\nu})^2 + \bar{\hat{\psi}} \left(i\partial\!\!\!/ + \hat{g}\hat{A\!\!\!/}^b \hat{t}^b + g_2 W\!\!\!\!/^a J^a \right) \hat{\psi}$$

$$\mathcal{L}_{c.n.} = -\left(\frac{R}{2} + \frac{1}{4} F^a{}_{\mu\nu} F_a{}^{\mu\nu} + i\bar{\psi}\partial_\mu \gamma^\mu \psi - e A^a_\mu J^\mu_a + \mathcal{L}_\pi \right)$$

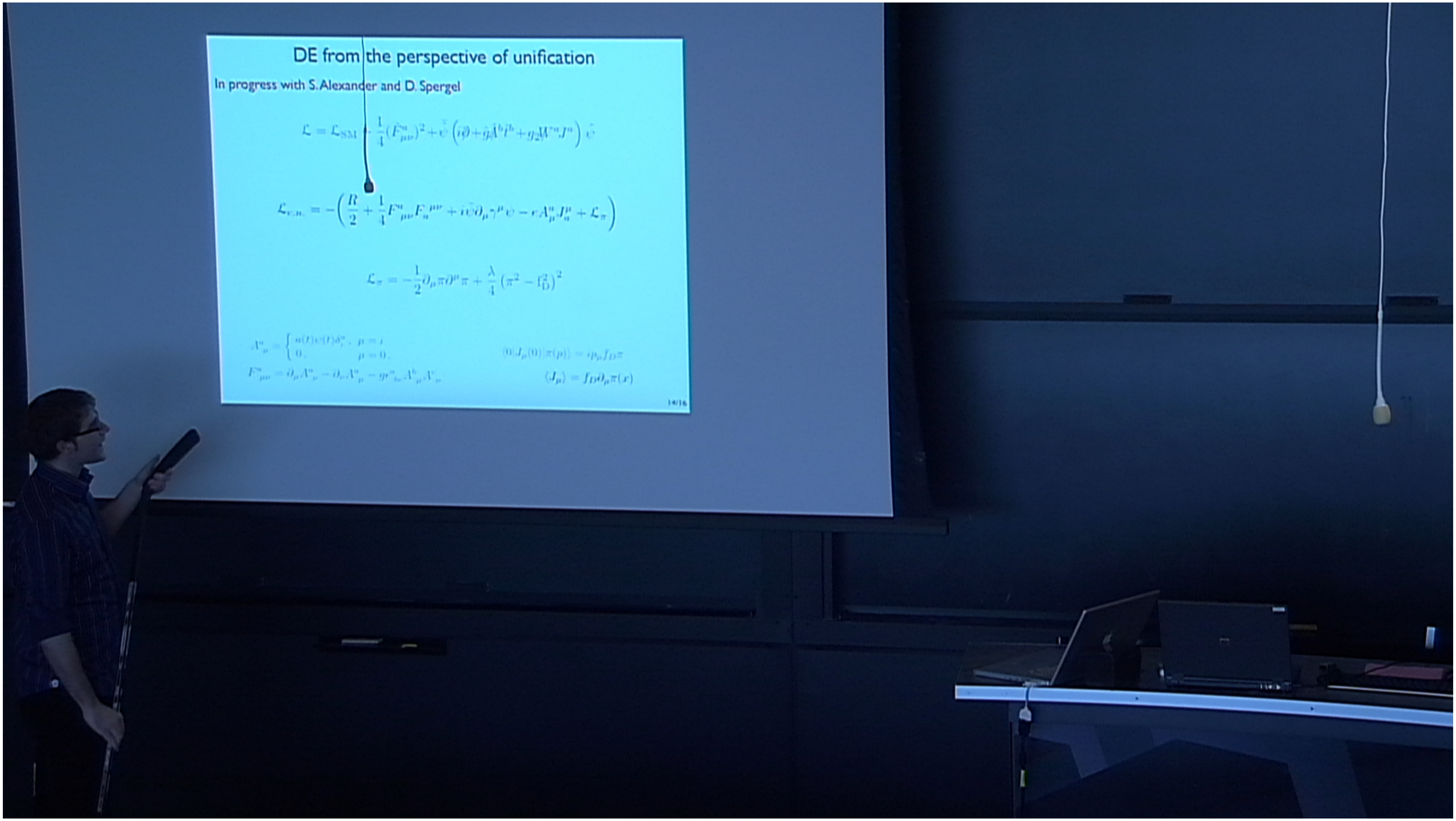
$$\mathcal{L}_\pi = -\frac{1}{2}\partial_\mu \pi \partial^\mu \pi + \frac{\lambda}{4}\left(\pi^2 - \mathrm{f}_{\mathrm{D}}^2\right)^2$$

$$A^a{}_\mu = \begin{cases} a(t)\psi(t)\delta^a_i \,, & \mu = i \\ 0 \,, & \mu = 0 \,, \end{cases}$$

$$F^a{}_{\mu\nu} = \partial_\mu A^a{}_\nu - \partial_\nu A^a{}_\mu - g\epsilon^a{}_{bc} A^b{}_\mu A^c{}_\nu$$

$$\langle 0 | J_\mu(0) | \pi(p) \rangle = i p_\mu f_D \pi$$

$$\langle J_\mu \rangle = f_D \partial_\mu \pi(x)$$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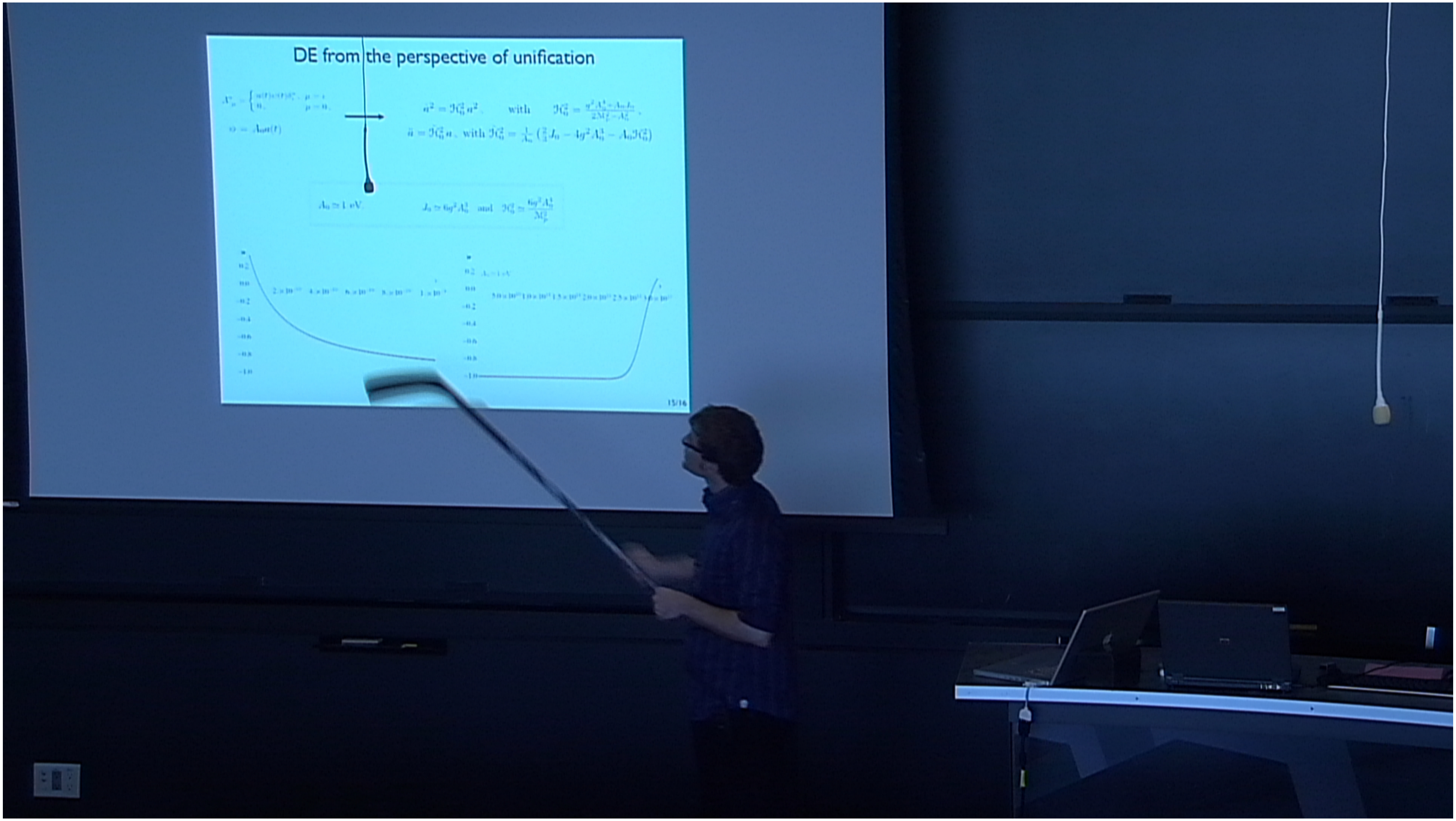
DE from the perspective of unification
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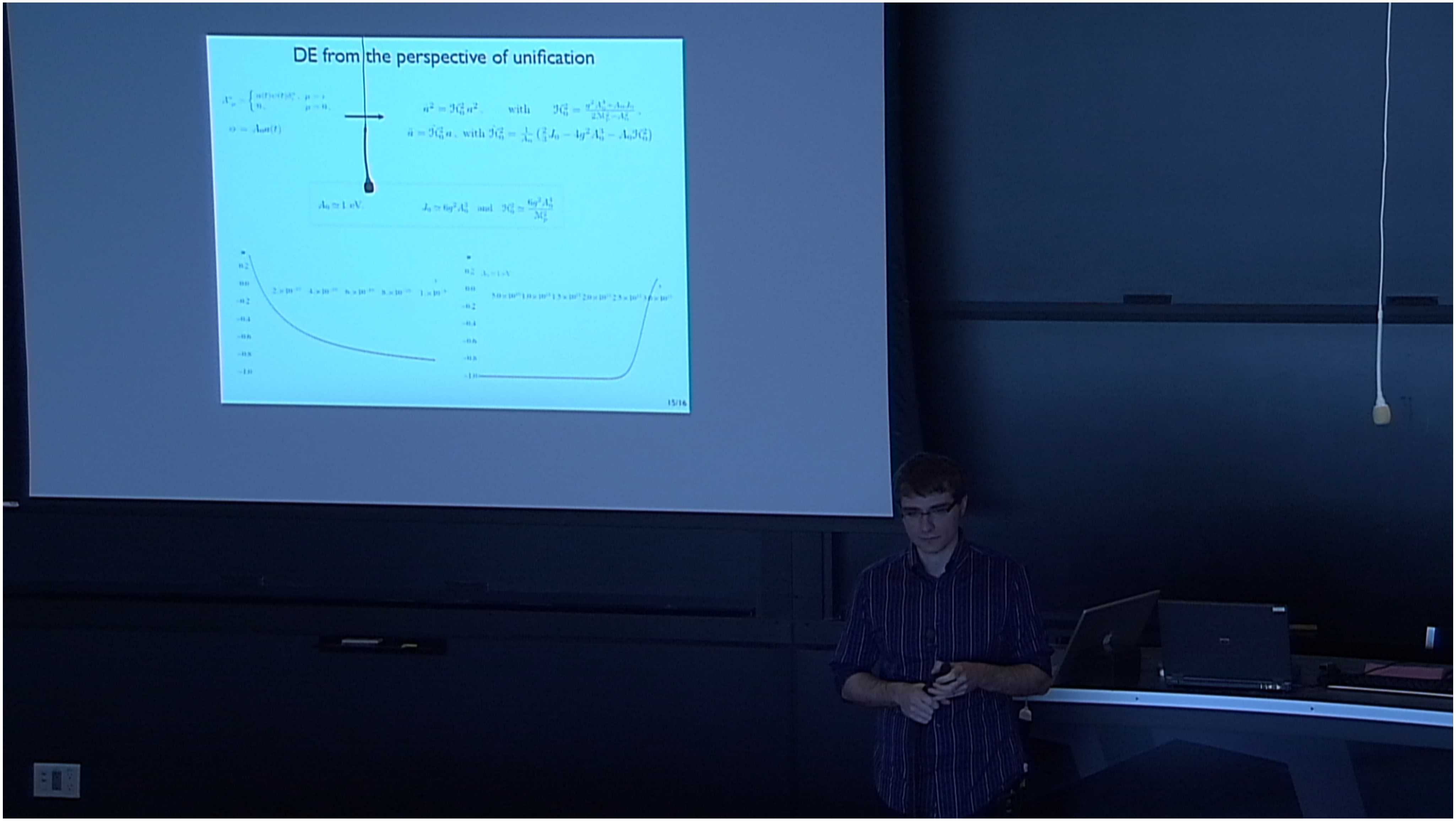
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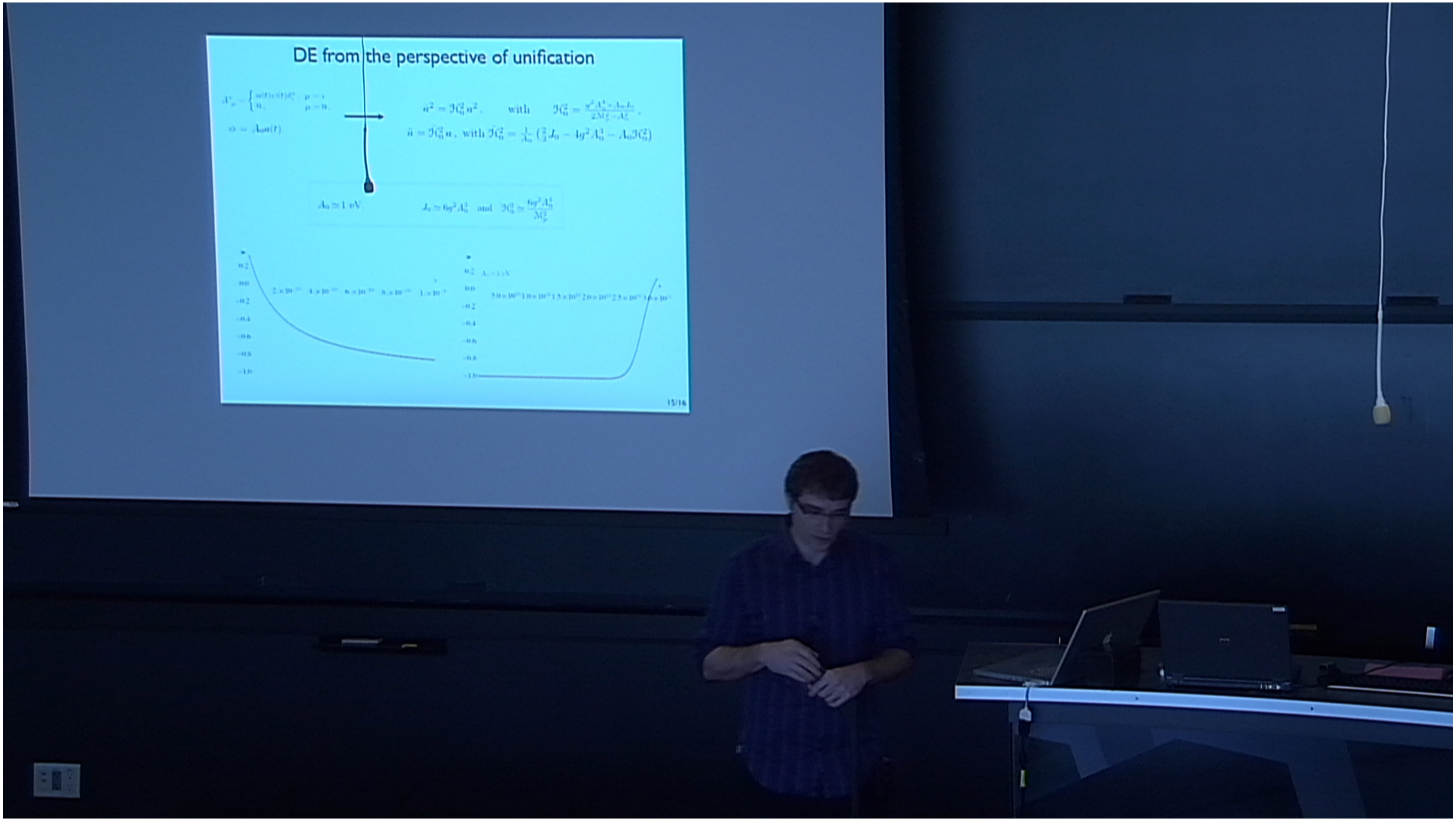
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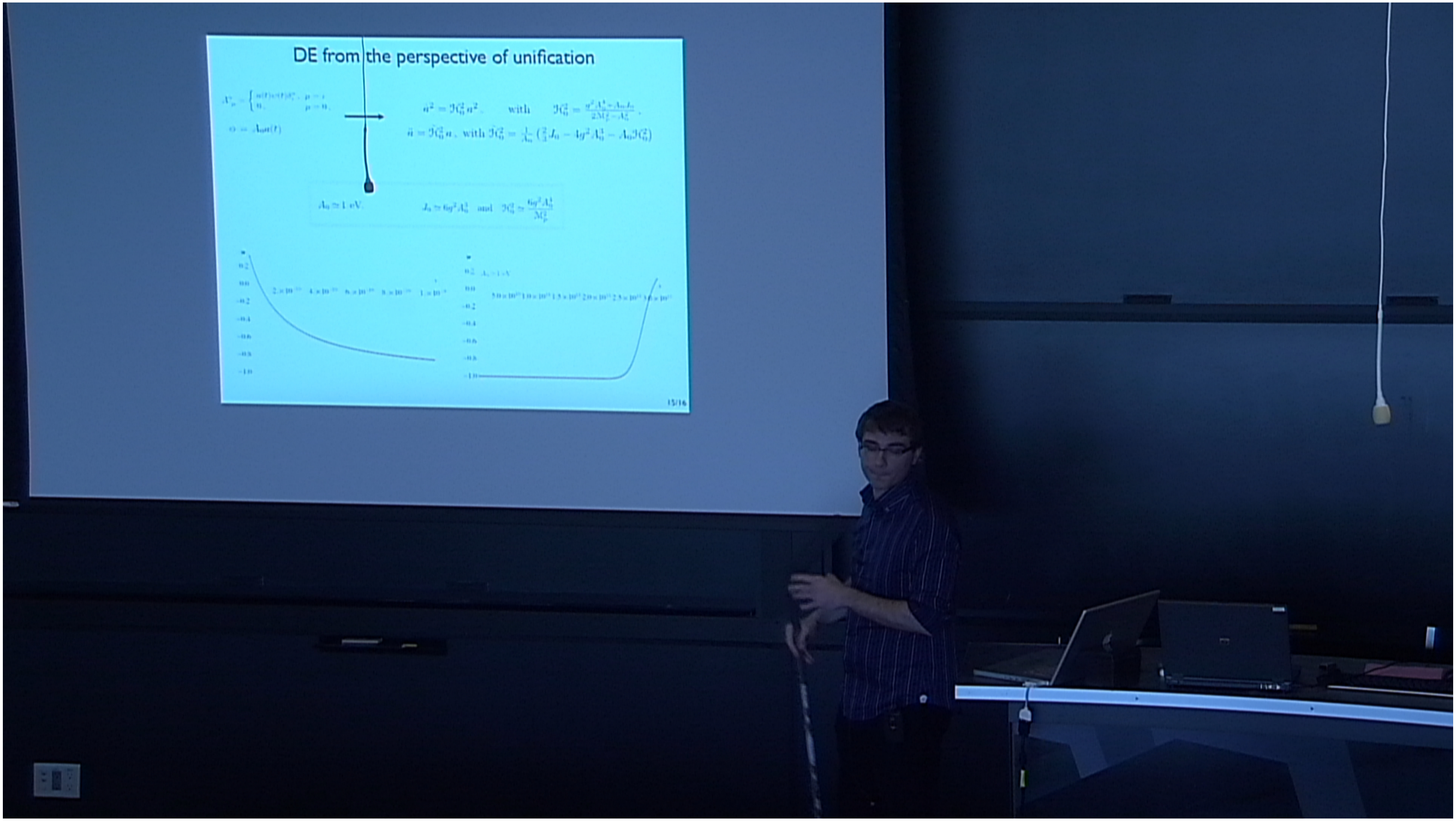
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